STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

ROCKFALL MITIGATION

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16. ABSTRACT

Rockfall has been reported along about 3000 miles of California highways. Information was obtained by means of a questionnaire sent to California Department of Transportation maintenance personnel and by field examination of 92 locations. Information contained in the questionnaire was used to examine the causes of rockfall in California, identify corrective methods that are used, and determine the effectiveness of these mitigation measures. Additional information on rockfall mitigation was obtained from a literature search and from correspondence with fourteen State Transportation Departments and with transportion systems in Canada, Switzerland, and France.

The data from California sites show that rain is listed as a cause of rockfall at all 92 sites. Glacial material and volcanic mudflows are common sources of rockfall in the State. Wire mesh fences are widely used in California to control rockfall. The effectiveness of these fences is dependent upon the use of design criteria developed by the Washington State Department of Transportation. A flow chart has been developed for use in choosing effective mitigation measures. These corrective methods are described in an appendix to the report.

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (1/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi) pounds per square foot (psf)	6895 47.88	pascals (Pa) pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ ($MPa\sqrt{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ ($KPa\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)

ACKNOWLEDGEMENTS

This research report is dedicated to Byron Works, Co-principal Investigator on this project. His untimely death, in May 1984, prevented him from completing this report. The other authors have tried to prepare text and illustrations that he would have endorsed.

We greatly appreciate the time and effort spent by maintenance personnel in all Caltrans Districts to provide us with data for this study. They have the burden of the rockfall problems and it is our hope that, by application, this report will help reduce that burden.

We would like to thank the various states that corresponded with us about rockfall. They are listed below.

1.	Alaska	8.	New Hampshire
2.	Arizona	9.	New Mexico
3.	Colorado	10.	Oregon
4.	Hawaii	11.	Utah
5.	Idaho	12.	Vermont
6.	Montana	13.	Washington
7.	Nevada	14.	Wyoming

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INTRODUCTION

The purpose of this research project is to determine the causes of rockfall in California and to formulate guidelines to most effectively deal with this problem for any given locality and situation.

Rockfall is a condition that has existed along the state highway system since its beginning. All of the 11 California Department of Transportation (Caltrans) Districts in the state have rockfall problems. Money spent by the state attributable to rockfall has totaled millions of dollars over the years. The annual cost of rock and sand patrol by maintenance personnel is approaching two million dollars. Claims filed against the state as a result of rockfall-caused accidents averaged over one million dollars per year from 1970 to 1975.

The diversity of geological features and climate within California result in a wide variety of rockfall situations. A survey has been made of each district to determine the extent of the problem. Rockfall control measures have historically been applied by maintenance forces familiar with the area. In many areas, design restrictions or lack of design considerations for rockfall mitigation have resulted in situations that can be eased only be extensive and expensive repair or redesign. Many cuts were made without the benefit of a prior geologic study that might have foreseen future rockfall problems. On some roads, there are many miles of cuts exhibiting the same tendency for rockfall.

Data were obtained from district personnel familiar with local problems of rockfall in order to: 1) document the extent of the rockfall problem; 2) determine the effectiveness of mitigation measures in use; 3) determine cost effectiveness of these measures; 4) recognize parameters controlling effectiveness of mitigation measures; 5) lay a framework for mitigation guidelines; and 6) suggest areas for further study. Physical measurements of various rockfall sites were obtained so that comparisons could be made.

The main body of information came from conversations with district maintenance and materials personnel and field investigations of representative sites. Additional data were obtained by inducing rockfall at selected locations. Correspondence with other state agencies, other states and foreign countries, along with a literature search provided much useful information. The data obtained from maintenance personnel and from field examinations of these same sites were stored in a computer data retrieval system. Comparisons of the effectiveness of mitigation measures with other factors were made by computer. Performance of mitigation measures were checked in an effort to determine under what circumstances certain mitigation measures would be effective. In-depth field testing of mitigation methods was outside the scope of this project.

Problems encountered in the research include difficulty of obtaining costs for mitigation measures, out-of-state travel restrictions, subjective estimates of the effectiveness of mitigation measures and maintenance requirements, and delays in the study in order to respond to other geotechnical problems of the districts.

Definition of Rockfall

For purposes of this report, "rockfall" is defined as the relatively precipitous movement of a segment of rock of any size from a cliff or other slope that is so steep that the segment continues to move downslope. Movement may be by free-falling, bouncing, rolling or sliding. Neither rock avalanches, in which large volumes of rock move downslope as a unit, nor landslides were encompassed in this study. The distinction between considerable rockfall at a given point and small avalanche was not a problem during this investigation because, in locations studied, the failure of rocks generally occurred as a series of individual events rather than as a mass movement.

Literature Search

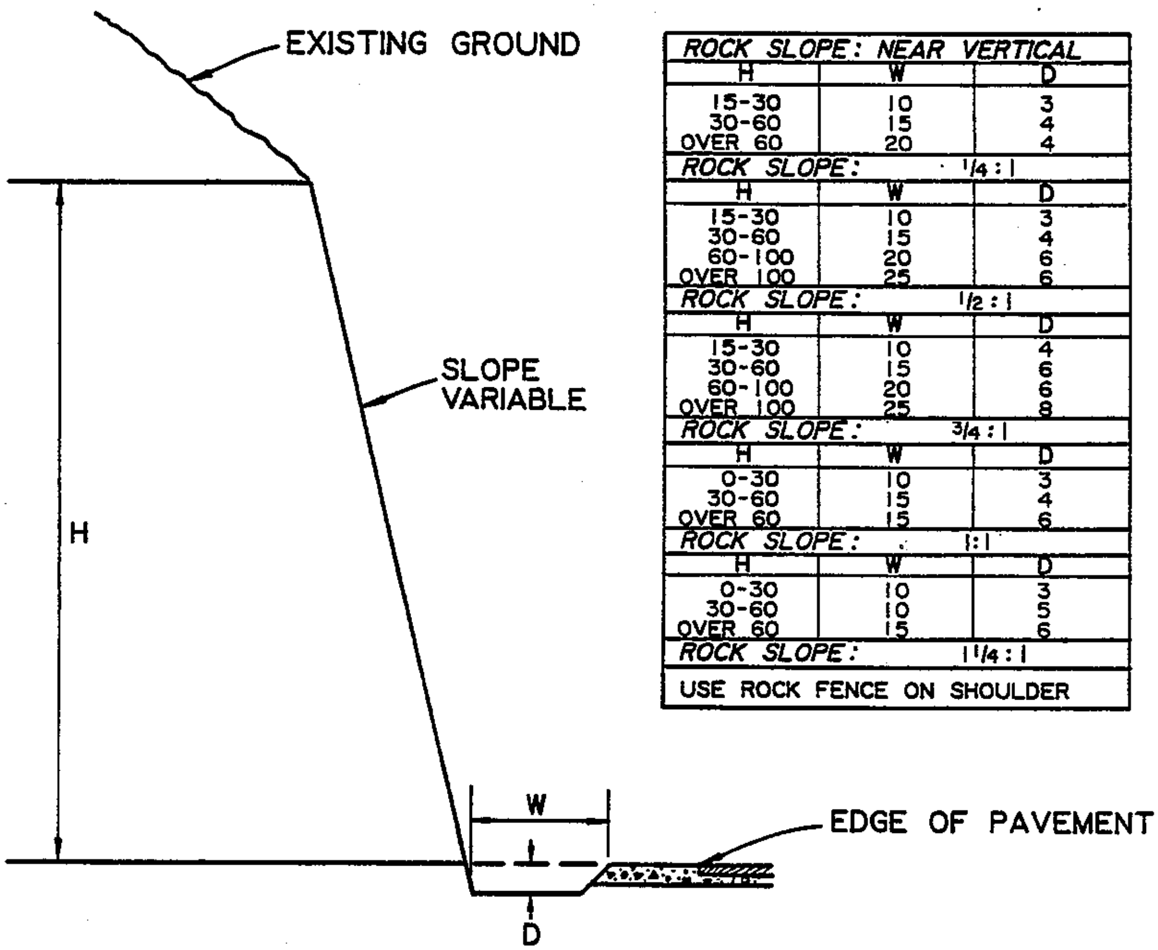
There has been a continuous search of the literature related to rockfall since the inception of the project. Numerous articles in the publications on rock mechanics and engineering geology are pertinent to one or more aspects of the subject. The diversity of both source and topic of the articles illustrates that each rockfall site is unique and requires a specific solution.

Nevertheless, we have found that three papers are directly applicable to this research project and they have been relied on heavily for background material, ideas, and organization of the study.

The first article entitled, "Evaluation of Rockfall and its Control," by Arthur M. Ritchie, appeared in Highway Research Record No. 17 in 1963. In this study, done by the Washington State Department of Transportation, it was reported that falling rocks obey certain physical laws and that the maximum distance a rock will fall from a given slope can be approximated. From this data, a table showing the relationship of variables in ditch design for rockfall areas was prepared (see Figure 1). This is referred to as the Ritchie Criteria in our report. The applicability of the Ritchie Criteria was verified in this study and had been thoroughly checked in 1969 during the correction of a specific rockfall problem (Mearns, 1976). Most other states indicated in their correspondence with us that they also apply the Ritchie Criteria.

Another paper that has been extremely useful during this study is entitled, "Treatments and Maintenance of Rock Slopes on Transportation Routes," by F. L. Peckover and J. W. G. Kerr(1977). Rockfall mitigation measures are discussed and illustrated. There is also a section on developing an effective program for dealing with rockfall.

The third significant publication is Rapport de Recherche LPC No. 80 from the Laboratoire Central des Ponts et Chaussees entitled, "Eboulements et chutes de Pierres sur les Routes." The first part of this report describes a method of mapping rockfall areas and assigning levels of risk to each problem that is identified along the route. The second part describes and illustrates examples of remedial measures that have been used on French roads.



H	W	D
ROCK SLOPE: NEAR VERTICAL		
15-30	10	3
30-60	15	4
OVER 60	20	4
ROCK SLOPE: 1/4 : 1		
15-30	10	3
30-60	15	4
60-100	20	6
OVER 100	25	6
ROCK SLOPE: 1/2 : 1		
15-30	10	4
30-60	15	6
60-100	20	6
OVER 100	25	8
ROCK SLOPE: 3/4 : 1		
0-30	10	3
30-60	15	4
OVER 60	15	6
ROCK SLOPE: 1 : 1		
0-30	10	3
30-60	10	5
OVER 60	15	6
ROCK SLOPE: 1 1/4 : 1		
USE ROCK FENCE ON SHOULDER		

RITCHIE CRITERIA
(After Ritchie, 1963)

Figure 1

CONCLUSIONS

- California has about 3000 miles of roadway along which rockfall occurs.

- Glacial material is a widespread source of rockfall in the Sierra Nevada. Fine material erodes and removes support for the boulders.

- The Mehrten Formation, composed of volcanic mudflows, andesites, and tuffs, is a major source of rockfall in California.

- Talus slopes are very difficult to stabilize once they have been disturbed.

- Rain is a primary cause of rockfall in California.

- Rolling rocks up to two feet in diameter may be restrained by wire mesh fence.

- Bouncing or free-falling rocks up to 1-1/2 feet in diameter may be restrained by wire mesh fence.

- Many wire mesh fences have been installed in California at distances from the toe of slope that do not provide maximum protection of the roadway.

- Many wire mesh fences in California have a gap between the bottom of the fence and the ground that allows rocks to roll under the fence and onto the traveled way.

- A flow chart can be used to choose effective mitigation measures.

- The extent of sites in California that experience rockfall warrants a systematic program for dealing with rockfall.

RECOMMENDATIONS

- A program to prioritize rockfall sites for repair should be instituted by Caltrans.

- The program should be developed by an interdisciplinary committee composed of geotechnical, maintenance, and project development personnel.

- The program should be administered by the Division of Highways Maintenance.

- The criteria developed by the Washington State Department of Transportation (Ritchie) should be used to design catchment areas for rockfall.

- Greater use should be made of mitigation measures other than wire mesh fences. Appendix A can be used as a guide.

IMPLEMENTATION

Implementation of knowledge obtained during this project has already begun by processing requests for reviews of rockfall areas from the districts. The report will be distributed to all Caltrans Districts and to other agencies, states and countries that have indicated an interest. Consultation with personnel engaged in designing rockfall mitigation measures has occurred and is expected to increase. Maintenance personnel have requested surveys of sections of highways to point out areas that may have rockfall and asked for suggestions as to how it may be mitigated. Specific sites have also been investigated at the request of district personnel engaged in the design of slopes in areas subject to rockfall. Information collected in this study has served as background material for litigation involving rockfall.

ROCKFALL - A GENERAL DISCUSSION

Rockfall occurs in areas that are subject to various types of external and, in some instances, internal forces. The source terrain may be natural topography or man-made, and the behavior of moving rocks varies according to a number of controlling factors. General causes of rockfall and factors influencing their behavior are listed in Figure 2a and 2b.

Cause of Rockfall

In this study, maintenance personnel throughout California were asked to list the causes of rockfall at the 92 sites investigated. Their responses are contained in Figure 3. It was noted that very little or no rockfall occurs when maximum temperatures are below the freezing point. Although earthquakes were not given as a cause of rockfall, it is well documented that such events can cause a large amount of rockfall for any one event. A description of the rockfall along Route 178, resulting from the Kern County earthquakes of 1952, is contained in Bulletin 171, California Division of Mines and Geology, in the chapter on Highway Damage written by O. W. Perry (1955).

Rainfall

The greatest amount of rockfall occurrences are during severe rainstorms when the fine-grained supporting particles of material are washed away from beneath larger rocks and the resistance to movement is overcome by gravitational forces. This failure process holds true for channeled runoff, snowmelt, springs and seeps. The frequency of

Causes of Rockfall

- Rainfall
- Geologic Features
- Differential Erosion
- Swelling Clay
- Freeze-thaw
- Wind
- Channeled Runoff
- Snowmelt
- Springs and Seepage

Figure 2A

Factors Influencing Rockfall Behavior

1. Site Conditions

   - Slope Height
   - Slope Angle
   - Slope Evenness
   - Vegetation
   - Presence or Absence of Bedrock or Hard Individual Rock

2. Rock Characteristics

   - Soundness
   - Size
   - Shape
   - Angularity
   - Elasticity

Figure 2B

	Causes of Rockfall	Number of Locations
1.	Rain	92
2.	Freeze-thaw	65
3.	Fractured rock	37
4.	Wind	37
5.	Snowmelt	25
6.	Channeled runoff	20
7.	Adverse planar features	16
8.	Burrowing animals	5
9.	Differential erosion	4
10.	Tree roots	2
11.	Springs or seeps	2
12.	Wild animals	1
13.	Truck vibrations	1
14.	Soil decomposition	1

Figure 3

Causes of rockfall for 92 sites from responses of Maintenance personnel.

rockfall during storms is reflected in the practice of some maintenance territories to constantly patrol the roads for rocks during storms.

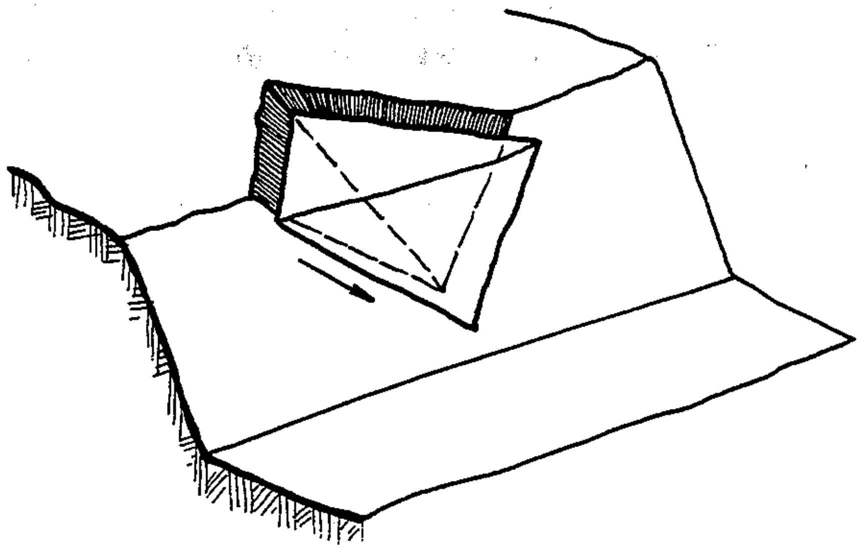
Geologic Features

Geologic features of certain types of rocks can make failure possible. Intensely fractured rock is very sensitive to forces that induce rockfall. Spacing of discontinuities in rock determines the size of rock that may fall, while orientation determines shape and susceptibility to fall.

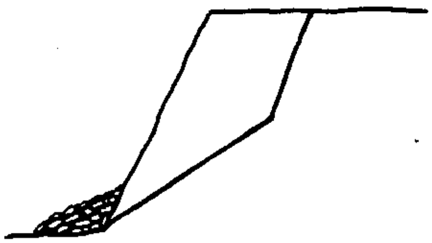
In many man-made cuts, wedge-shaped failures are common (see Figure 4). These are generally caused by undercutting the line of intersection between two intersecting planes at time of construction. Rockfall may then occur at a subsequent time, caused by cutting a steep sided ditch at the toe of cut. If the cut removes the support of intersecting discontinuities, a failure may easily progress to the top of cut and become larger with height, depending upon orientation of the discontinuities. Such blocks may become unstable upon the percolation of moisture into the boundary planes. These boundary planes usually contain clay that loses friction and cohesion when wet. They are also susceptible to the action of freeze-thaw. Long, weak planes oriented parallel to the road and dipping out of the cut can also lead to very large rock failures by the same process.

Differential Erosion

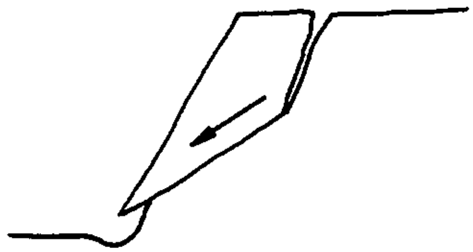
Deposits of material that are resting on one another commonly have differing resistance to erosion. Occasionally, a bed of material susceptible to erosion underlies a more



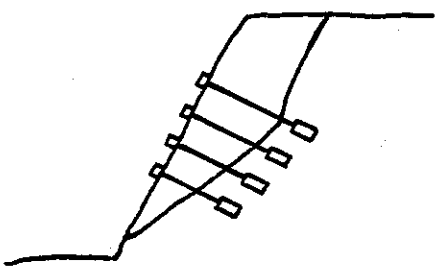
WEDGE BLOCK FAILURE



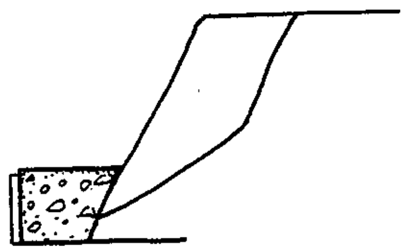
WEDGE-SHAPED FRACTURE SECURED BY TALUS AT TOE



DITCHING AND REMOVAL OF TALUS UNDERCUT SUPPORT OF WEDGE - MOVEMENT INITIATED



POSSIBLE ROCK ANCHOR SUPPORT



POSSIBLE ROCK BUTTRESS SUPPORT

WEDGE FAILURES

Figure 4

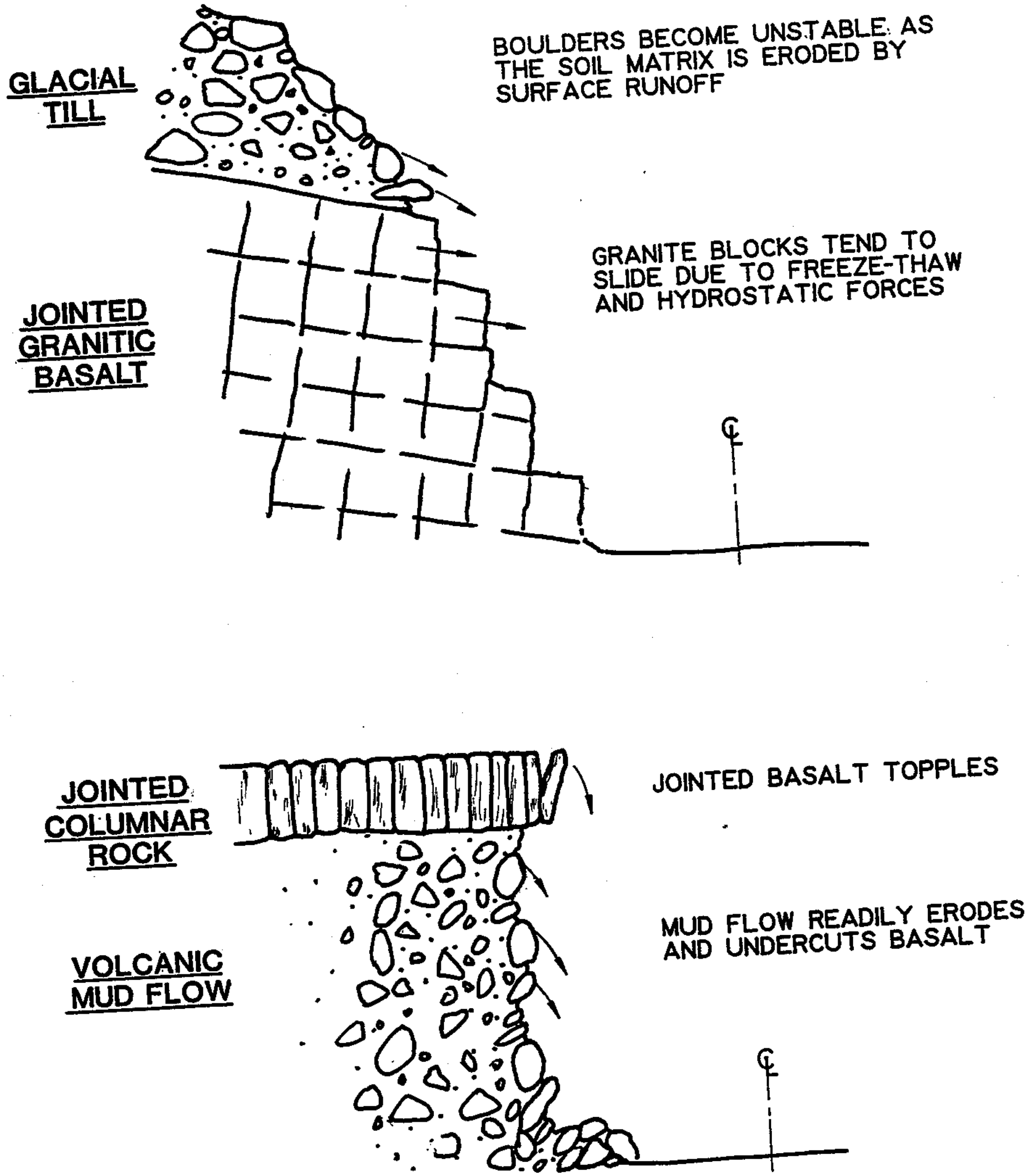
resistant bed, such as volcanic ash underlying a fractured volcanic flow rock (see Figure 5). Differential erosion results in the underlying material being eroded by the action of wind and water to the extent that the fractured overlying material is no longer supported, breaks off and moves downslope by gravitational force.

Unconsolidated or weakly consolidated deposits such as talus slopes, alluvium, deposits from glacial action and ocean and lake terraces can be the source of rockfall from natural slopes if they are on a slope sufficiently steep to allow rocks to travel downslope upon being freed by erosion.

Rockfall also occurs from deposits in which the hard rocks are held by a matrix that is subject to weathering. The difference in erosional rates between the matrix and the enclosed rocks will eventually lead to rockfall. Conglomerates and volcanic mudflows are the source of rockfall in some areas of California (see Figure 5).

Swelling Clay

Rockfall may be caused by swelling clays exposed to moisture in newly-constructed cuts. Sections of the material can slough off or a zone of this material can undermine overlying, more competent material. An example of this type of rockfall is in Inyo County on Route 190, post mile 66.2. Some of the volcanic rock has been altered almost completely to montmorillonite clay which sloughs due to the volume change that occurs with increase in moisture. This action undermines overlying material as well, leading to rockfall.



DIFFERENTIAL EROSION CAN LEAD TO UNSTABLE SLOPE CONDITIONS AND ROCKFALL

Figure 5

Freeze-thaw

Freeze-thaw cycles are a major cause of rockfall in California. In the higher altitudes, water percolates into the openings surrounding the blocks of rock, then freezes and expands when the temperature drops at night. The frozen water is capable of producing stresses strong enough to move the rock. When the sun warms the slope, the ice melts and the rock is free to react to gravitational forces. It should be noted that in some areas during the winter, the temperature does not get high enough or the time span is insufficient to complete the freeze-thaw cycle. The critical months for these forces to occur is during the late fall-early winter and late winter-early spring months. Of the 92 sites investigated, 79 are subject to temperatures that drop below freezing. Of these 79 locations, 14 were listed as having no problems with rockfall due to freeze-thaw. Most of these locations are estimated to have 45 or less days of freeze-thaw during the year. However, two locations having an estimated 30 days with temperatures below freezing were thought to be subject to at least some rockfall due to freeze-thaw. One location of only 10 days with temperatures below freezing was listed as having some rockfall due to this cause.

Wind

Wind is capable of causing rockfall by removing small particles that support larger material. Wind is frequently funneled through canyons, and it is in canyons that highways are frequently built. High velocity winds are common at times in the southern part of California. Steep cuts are more susceptible to wind-related rockfall than flatter cuts because there is less material supporting the rock. In most California locations, cuts become very dry during the summer, and the resulting loss of cohesion enables wind to blow away fine-grained particles. Wind has also been cited as the cause of rockfall in the oversteepened soil zone at the top of cuts where roots are exposed. Wind in the foliage can cause movement in the root zone, thus loosening the material and causing rockfall. Therefore, in locations where winds occur, especially during the dry season, rockfall can occur.

Channeled Runoff

Channeled runoff causes rockfall by undercutting the sides of the channel and by removing material in the bed of the channel. Channels may be formed in cut slopes as the result of insufficient or faulty drainage in the natural ground above the slope or on the cut slope benches. Channels may form on cut slopes due to the configuration and the height of the cut. These channels become larger with time as the material is eroded. Natural channels that are intersected by cut slopes may require protection from water erosion caused by the concentrated flow and/or increased velocity of water at that particular location.

Snowmelt

Snowmelt is a source of water that erodes the slopes. The period of time that it contributes water to the slope depends upon the amount of snow available and the air temperature. Snowmelt can be a factor during the time that freeze-thaw is effective in causing rockfall. Typically, snow disappears more rapidly from the slopes in road cuts because, due to relative steepness, they generally do not receive the depth of snow that the natural slopes do. Orientation of the slopes in relation to the rays of the sun and the ability of the earth and rock to absorb heat from the sun are factors influencing the time required to melt snow. Melting snow keeps the underlying material saturated over a period of time so that small slip-outs can occur. Individual rock failures can occur due to the removal, by running water, of the smaller particles supporting the rocks and by sloughing of the fine material surrounding larger rocks. However, a blanket of snow acts as a deterrent to rockfall because it helps to insulate the underlying material to keep it at a constant temperature and also helps to support the individual rocks. Soft snow on the slopes also slows the rock after it begins to move. However, if the snow is frozen on the surface, the traveling rocks may slide on the surface. This problem occurs in areas where snow removal operations build up a large amount of snow at the toe of a high steep slope. Snow can then melt and expose rocks near the upper part of the slope but may be frozen near the road level. When the mitigation measure (usually a fence) is covered with snow, it becomes useless.

Springs and Seepage

The effect that these sources of water have on slope erosion and subsequent rockfall is somewhat similar to that of melting snow. Springs and seeps may be encountered at any locality in a slope and, in California, are usually limited to rather small areas. The erosion of the slope around these wet zones often leads to considerable rockfall originating above and below the source. When these zones are encountered, rockfall may occur from the immediate zone of wetness. The source of rockfall then progresses upslope because of the removal of support to overlying material. The formation of an oversteepened slope above the wet area is a common result in addition to rockfall. Rockfall may progress downslope from the source by the saturation and consequent reduction in cohesion and friction in the material, and also by the removal of fine-grained material by running water that supports larger fragments of rock.

Other Causes

Burrowing animals, animals walking across or at the top of cut slopes, sonic booms, truck vibration and tree roots are other causes of rockfall in California. Animals burrowing under rocks have loosened the soil sufficiently to cause the rocks to move downslope. They also loosen the soil so that other erosional processes, such as wind and rain, can cause rockfall. Deer and other animals have been cited as the cause of rockfall when they knock rocks loose as they travel along trails or wander on cut slopes. Rockfall has also been attributed to shock waves from sonic booms caused by military aircraft during training exercises in eastern Inyo County. Tree roots can exert considerable lateral force as they grow and thus pry rocks out enough to cause rockfall. Earthquakes have caused significant rockfall on roads in steep terrain even though this was not listed on any questionnaire as a cause of rockfall. Earthquakes in the Long Valley area of Mono County in 1981 disrupted many rocks in the steep canyons in the region and large boulders moved downslope. Rockfall resulting from the Kern County earthquake of 1952 closed Route 178 for several months (California Department of Natural Resources, 1955).

In summary, there are a variety of reasons that cause rocks to fall. The two main causes of rockfall that were reported are rain and freeze-thaw. It should be noted that there are other variables to consider in evaluation of rockfall areas such as slope height, slope angle and size of rock. These and other parameters will be discussed in the segment of the report dealing with performance of mitigation measures.

Factors Influencing Rockfall Behavior

Numerous factors influence the behavior of rocks after they have begun traveling from their points of origin (see Figure 2B). Many of these factors were observed during an induced rockfall program, others were related to the researchers by maintenance personnel and a few were observed during a resloping operation on a large slide on the Pacific Coast Highway. These factors may be grouped according to site conditions and to individual rock characteristics. Both groups influence travel speed, mode of travel, distance traveled and resistance to disintegration. These factors have a direct bearing on the design of mitigation measures for any particular site.

Site Conditions

Site conditions that affect rockfall are: height of slope, steepness of slope, slope evenness, vegetation and the presence or absence of bedrock or hard individual rocks.

The height of the slope affects the velocity that rocks may attain before contacting an obstacle, the mitigation measure or roadway. It also influences the number of times a rock may bounce as it gathers speed, and therefore, the distance from the slope that the rock may impact the roadway. The speed also controls the propensity of the rock to disintegrate as it moves downslope. Disintegration is accompanied by an increased speed and change of travel direction of one or more fragments that can result in rock impacting much further out from the slope than if the rock had stayed intact.

The steepness of the slope affects the speed of the rock, and it also helps to determine whether or not the rock will slide, roll, bounce or free-fall.

Evenness of the slope affects the lateral and vertical travel path of the rock. The speed of the rock is also influenced by the obstacles that the rock may strike. On uneven slopes, the rock may be launched into the air by sloping shelves, other rocks, outcrops or erosional features. The traveling rock will tend to stay closer to the slope on an even slope. A very uneven slope can slow rocks and channel them into narrow depressions on the slope; however, the greater the speed and size of rock, the more difficult it is to change its initial travel path.

The hard surface on slopes where bedrock or large hard rocks are exposed will cause impacting rock to rebound away from the slope face. If most of the rocks on a slope are small in relation to the traveling rock, the speed of the rock may not be significantly affected. However, if the opposite is the case, the speed of that rock can be significantly reduced.

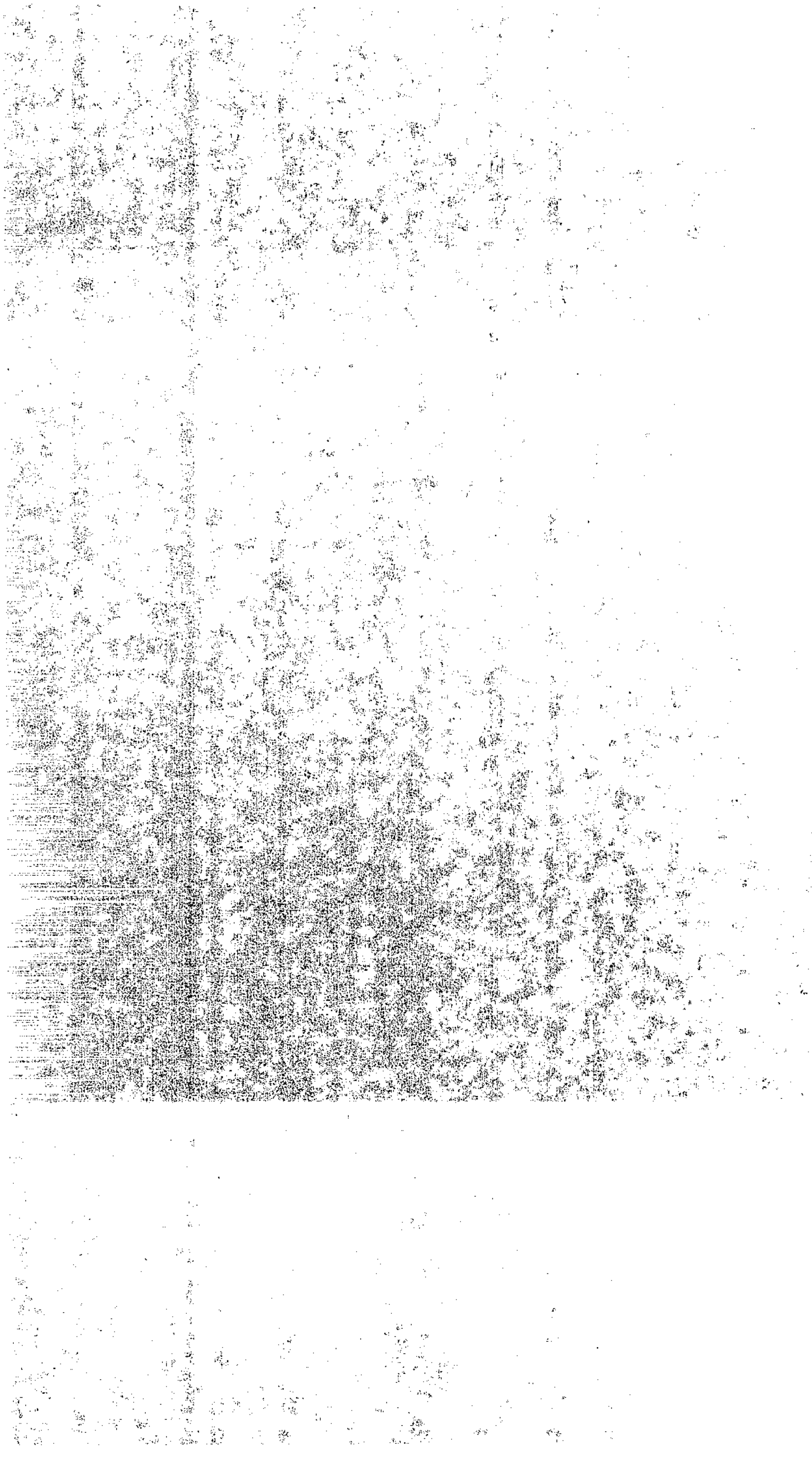
Vegetation helps to reduce rockfall by catching and holding rocks, by slowing their speed and by binding the soil matrix together to prevent erosion and consequent movement of rocks. However, cut slopes that have continual rockfall will not sustain any significant amount of vegetation. There are natural slopes containing vegetation that still are sources of rockfall. The relation between the size of the rock and the size and thickness of the vegetational growth is important to the possibility of rockfall. In some locations, rockfall may originate in brushy terrain or it may originate above a slope containing a considerable amount of vegetation, such as trees and brush. In these situations some rock will be stopped and slowed but some may continue to move downslope to the roadway.

Rock Characteristics

Rock characteristics that influence rockfall behavior are: soundness, size, shape, angularity and elasticity. The soundness of a rock will determine whether or not it will stay intact until it reaches the bottom of the slope. The size of the rock influences the distance and acceleration with which it will travel down a slope. A large rock will tend to roll over smaller rocks and thereby cause natural segregation on the slope. The shape of rocks influences their mode of travel and the tendency to continue movement after initial dislocation. Prolate rocks may begin movement by sliding, then rolling about the long axis. However, on a long slope with increased speed, they will cartwheel about the short axis with the ends of the rock striking the slope surface. The velocity of prolate rocks appears to be less than that of other shapes. Bladed and tabular rocks were also observed to travel with the long axis vertical to the slope.

Although evidence from this research project is limited, it appears that rounded rocks will begin to roll easier, roll further and faster than more angular rocks of similar size.

Very hard and sound rocks have a high modulus of elasticity and, therefore, will bounce higher and further (under similar conditions) than others. However, these characteristics were not part of this study and no other discussion of this property will be made.



ROCKFALL MITIGATION - A GENERAL DISCUSSION

The hazards from rockfall may be mitigated by slope stabilization, providing protection from the rocks, warning devices and by rock patrols (see Figure 6). No matter what method or combination of methods are used, the ability to entirely eliminate the hazards from rockfall in some locations may not be achievable from a monetary or environmental viewpoint. There are also the problems of recognizing particular rocks that may move downslope and of determining when that may occur. The expense and personnel needed to undertake this preliminary work is beyond presently available resources. Instead, the problem must be attacked as rockfall occurs using the method that best mitigates the problem at the most reasonable cost.

Stabilization of the rocks so that they cannot move downslope may be accomplished in a number of ways. Those methods that have been used may be grouped under the general categories of (1) Excavation, (2) Drainage, (3) Shotcrete, and (4) Support and Reinforcement Systems.

Protection methods include (1) Relocation, (2) Intercepting Slope Ditches and Berms, (3) Wire Blankets, (4) Wire Mesh Catch Fences, (5) Wire Mesh Catch Nets, (6) Shaped Ditches, (7) Catch Walls, (8) Rock Sheds, and (9) Tunnels.

Warning methods include (1) Patrols, (2) Electric Fences and Wires, (3) Surveying Methods, (4) Horizontal Measurement Devices, and (5) Signs.

Rock patrols are used as a method to remove the rock after it has reached the roadway.

ROCKFALL MITIGATION MEASURES

Stabilization	Protection	Warning
Flatten Slope	Relocate Roadway	Signs
Scale or Trim	Tunnel	Electric Fences and Wire
Design to Geology	Rock Shed	Monitoring
Controlled Blasting	Bench	Patrols
Subsurface Drainage	Catchment Ditch	
Rockbolts and Dowels	Widening at Grade	
Shotcrete and Gunite	Wire Mesh Fence	
Anchored Wire Mesh	Steel H-Beams and Timber Lagging Walls	
Cable Lashing	Metal Guardrail	
Concrete Buttresses	Jersey Barrier	
Retaining Walls	Earth Berm	
	Draped Mesh Blanket	

FIGURE 6

Rock Stabilization

Excavation

Excavation methods at time of initial slope construction can greatly reduce rockfall potential found after the many causes of rockfall have affected the slope. Ideally, slopes are excavated on an angle in which no rockfall can occur. For some locations this is not practical from an economic or environmental standpoint. In locations where the rock is fractured, the probability of rockfall can be reduced by making a joint survey of the discontinuities and applying the results of the analysis to the cut slope design. In locations where a hard layer that may produce rockfall is underlain by one that is susceptible to more rapid erosion but contains no rock, a bench may be provided at the line of contact between the two and measures employed to reduce the erosion rate of the softer material. In zones where loosely consolidated material containing rocks is encountered, a bench may be provided at the base of this material and the slope flattened in the zone of loose material.

Controlled blasting techniques such as presplitting to produce a smooth slope face in rock slopes can be quite effective to mitigate rockfall. The segments of rock in a smooth excavation help to support the overlying and adjacent rock segments so that the slope face acts more as a unit rather than as a number of individual rocks. Presplitting is generally confined to slopes 3/4:1 or steeper because at lower angles, it is too difficult to line up the drill holes so that they are parallel to each other and an irregular slope will result.

Benches placed at regular intervals help to contain rockfall. Access to these benches should be provided so that they can be cleaned when the rock debris begins to build up to a point where the bench becomes less effective. Benches also reduce the volume of runoff in the lower areas of the slope and thereby reduce the rate of erosion and rockfall. They also provide a measure of safety for construction personnel as they excavate the slope. Benches should have a minimum width of 20 feet. Extra width at road level should be provided in zones where preliminary investigation indicates that rockfall may develop. It may be necessary to construct a catchment ditch or install barriers of some type at a later date. The extra width will increase the chance for rocks to impact the ground before entering the traveled way in any case. This width should also be at least 20 feet.

Excavation methods used after the cut has been in existence for some time include flattening the slope, removal of unstable material, trimming sections that may be sources of rockfall, scaling, steepening the slope to provide extra width at grade and bench removal to obtain extra width at grade. Flattened slopes should preferably be excavated to an angle such that rocks will not travel down the slope. The next most preferable choice is to excavate to an angle where the rocks will not bounce down the slope and so that they can be stopped at road level before they enter the traveled way.

Sometimes a localized unstable area is a potential source of rockfall that can be removed by excavation. Caution should be used so that the rockfall source is not buttressing adjacent material that could become a larger problem than the existing one.

Some slopes may contain irregular protuberances or ledges that are the source of rockfall. These may be on natural or man-made slopes. Localized excavation by blasting may solve the problem.

Scaling slopes by hand or with equipment is generally helpful for only two or three years. Maintenance forces are limited by California safety regulations; therefore, scaling on steep slopes must usually be performed by a contractor skilled in this line of work. The short time span that scaling is useful is due to the type of material and conditions that lend themselves to scaling. To successfully scale a slope, the rocks must be in a weak matrix that erodes and, thus, exposes new rock; or the rock is separated by numerous discontinuities to such extent that scaling can be useful; or there are individual loose rocks resting on ledges of bedrock. The latter example is commonly found on slopes that were overshot during construction or where freeze-thaw in an irregular face has caused rocks to move a short distance. Scaling of natural slopes, such as glacial deposits, above the road could encompass extensive work due to the large area that may be involved.

A slope may be steepened in order to provide extra width at road level for a catchment ditch or barrier installation provided the material is competent enough to preclude sliding or developing rock avalanche. Slopes that are steepened will reduce the distance from the slope face that rocks bounce and, therefore, affect the width at grade in which rocks will impact. Less width at grade is required for near vertical slopes than those between 1/2:1 and 1:1(Ritchie, 1963). Many cut slopes have been constructed on an angle that is overly flat in the bottom section of the cut where the fresher rock is exposed, while the top section of the cut in the weathered zone may be the source of rockfall. Another situation in which steepened slopes may be used is in the case of sedimentary material such as glacial deposits overlying bedrock. The glacial material, subject to constant erosion, is the source of rockfall. If the underlying bedrock can be steepened to provide a catchment zone for the eroding material, the problem is mitigated to a great degree and may be made much more effective by constructing a shaped catchment ditch at the toe of slope, installing a barrier fence if needed, and perhaps constructing a bench along the base of the erodible material.

Slopes in which there is an existing bench may be resloped to gain extra width at grade by removing the bench. The extra width at grade can be utilized to construct a catchment ditch or a barrier to stop rocks from entering onto the roadway if the rocks are quite large. This method was used on Route 80 in the Sierra Nevada (Mearns, 1976).

Drainage

Good surface and subsurface drainage can significantly reduce rockfall in many situations. Drainage is intended to reduce the amount of water that can loosen and transport smaller particles of material that support larger rocks. Subsurface drainage also reduces pore water pressure that may cause failures. Proper drainage at the time of initial construction can save much maintenance and, perhaps, reconstruction at a later date. Proper drainage is generally more important for areas in which the rock is easily eroded from the slope than where hard bedrock is exposed. However, pore water pressure can cause large failures in bedrock. Surface drainage methods include: (1) drain any depression above the slope that can collect surface runoff, (2) reshape the ground surface above the rockfall area to provide runoff to the flanks of the slope, (3) seal or plug permeable areas and cracks above or within the slope, (4) construct lined ditches, install culverts and drains to divert and carry surface water from the problem area.

Depressions that can collect runoff often are an indication that the area is the site of an old landslide that may be reactivated upon becoming sufficiently saturated. They also may be due to faults - as old erosional features. These depressions may or may not store water, depending upon permeability of the surface mantle. If water is not being stored, it may be an indication that surface water is rapidly entering the slope and, perhaps, contributing to the rockfall problem at lower elevations. The amount of surface water that may run into such depressions can be compared to the amount stored for a rough idea of subsurface permeability. If the water is being stored on the surface, the time required for the water to percolate into the ground may take longer but the end result can be the same. The slopes above the cut should preferably be inspected immediately after a good rain during a wet season so that the worst conditions are easily observed.

It may be necessary in some cases to do some reshaping of terrain above the rockfall area so that surface water will drain to the sides of the problem area.

Permeable areas above the rockfall slope, such as sand or gravel zones or possible cracks formed by a slide, should be sealed by paving, plastic sprays and/or filling with impermeable material to minimize infiltration of surface water.

Drainage ditches above the rockfall zone should be lined with asphalt, gunite, plastic sheeting, or concrete if the permeability of the ground is significant. If there is significant gradient that would produce considerable erosion of material, the water should be carried away by culverts or other covered drains.

Vegetative cover is very useful to minimize rockfall provided the drainage is adequate. While vegetation reduces water in the soils by transpiration, it also encourages penetration of water into the soil zone. Vegetation also helps to bind material together in the soil zone and thereby reduces the rockfall problem.

Spray-on plastics have been used on two test slopes in the Sierra Nevada in California. One was in fractured granitic rock overlain by moraine and the other was in granite rock that has disintegrated in varying degrees. Results indicated that there was a savings to maintenance when one of the two products tested was used. It is believed that respraying would be required during alternate years (Mearns and Hoover, 1973).

Subsurface drainage as applied to rockfall mitigation is limited to drain holes drilled nearly horizontal. Their purpose is to intercept subsurface water and direct it to the surface where it is carried away from the slope. The water table is lowered and the pore water pressure is thereby reduced. Generally, this method is used to prevent landslides, but it can also reduce rockfall associated with long-term landslides and rockfall associated with freeze-thaw as well as rockfall that may be the result of pore water pressure or seepage. In some instances, the problem of freeze-thaw can be greatly alleviated by installing a number of rather shallow horizontal drain holes in a rock face. Generally, the holes are aimed to intersect as many fractures as possible, but may be installed to tap an underground aquifer or saturated zone controlled by a fault or geologic formation. Such horizontal drains should be installed when ground water is encountered during construction of a slope. The collected water should be carried away from the slope in pipes and not be allowed to reenter the slope from open ditches.

Shotcrete and Gunite

Shotcrete is pneumatically applied concrete having a maximum size aggregate of 3/4". It has generally replaced gunite which is similar but has smaller aggregate. Shotcrete is used on rather sound and clean surfaces to reinforce a rock slope in which the individual rocks are, or will become, unstable by the various weathering forces. Dry rock surfaces are best to shotcrete, although Piteau and Peckover (1978) report that wet surfaces can be successfully treated with careful control of admixture and nozzle water settings. Wire mesh is used to reinforce the shotcrete and to help make the slope behave as a unit. The shotcrete is applied in layers three to four inches thick with time allowed for each layer to set before applying subsequent layers. Wire mesh should be anchored closely to the rock surface before applying the shotcrete. The more uneven the surface, the harder it is to apply the mesh and, therefore, obtain a good job of reinforcement.

The slope should be carefully scaled prior to application of shotcrete and the surfaces of the rock cleaned by air or water jetting if there is a coating of material, such as clay or mud, to which the shotcrete will not adhere. Peckover and Kerr (1977) believe that service benefits may still result even though the shotcrete is applied to dirty and broken surfaces which cannot practically be cleaned. The decision to shotcrete under these conditions must be based on experience, good judgment and a degree of luck.

Fookes and Sweeney (1976) discuss gunite and recommend that the mesh be dowelled to the surface to accommodate irregularities in the face. For heavier restraint, the mesh could be supported by rock bolts. The wire mesh is typically electrically welded 100 mm (4") square and Number 9 standard wire gage.

Lang (1972) states that shotcrete can be very effective and safely used in situations where conventionally placed concrete or other material is impossible to use. He states that it can also be used to build up structural members and to span over a large seam or to span between rock bolts which hold a rock mass together. Since these zones can range up to 10 feet, the shotcrete should be reinforced. Treatment consists of cleaning out the zone to the required depth over the full width to sound rock on either side, and filling the "dental" excavation with reinforced shotcrete or gunite which is tied to the sound rock on either side with rock bolts. This method can be applied either to a local pocket or to a continuous zone that cuts completely across the excavation being made.

Gedney (1970) suggests using shotcrete to prevent deterioration in thin shale beds separated by other sedimentary beds less subject to weathering.

Shotcreted surfaces can deteriorate due to frost action, ground water seepage or rock spalling due to lack of shotcrete bond. Peckover and Kerr (1977) report that West German Railways have applications over wire mesh reinforcing which have been in use for 45 years and have an expected life of 70 years.

It is most important to provide weep holes to prevent the buildup of pore water pressure. The drains are generally short, flexible plastic pipes placed in cracks or holes drilled into water-bearing rock. Longer horizontal drains should be drilled and installed prior to applying shotcrete if there is a considerable flow of water. The installation of shotcrete with the required drain holes is expensive. Several years ago weep holes cost on the order of $30 to $50 each and shotcrete installed varied from $280 to more than $500 per cubic yard (Peckover and Kerr, 1977).

Specifications for materials, proportioning and application of shotcrete (ACI 506.2-77), adopted as a standard of the American Concrete Institute in August 1977 may be obtained from that Institute by written request.

Support and Reinforcement Systems

Supports are designed to resist loads placed on them and are generally required in locations where there is the possibility that one or more large blocks may fail. In some cases, a few rocks supporting a large quantity of material may require support to prevent a rock avalanche or a continual rockfall problem. Supports provide passive resistance to movement and include retaining walls and buttresses. Fookes and Sweeny (1976) also list nonrigid buttress systems such as crib walls, soil or rockfill berms and stone-filled gabions as possible supports. Support systems are installed with the least amount of disturbance possible to the rock they will support. Adequate drainage should be incorporated so that buildup of pore water pressure and the effects of freeze-thaw action do not occur between the structure and the rock.

Reinforcement systems add strength to the rock mass by increasing the frictional or shear resistance. Lang (1972) restricts rock reinforcement to the use of rock bolts and their accessories, such as wire mesh, rock bolt ties and shotcrete. The reinforced rock becomes a competent structural entity either on its own or as a part of a composite structure. Piteau and Peckover (1978) include cable lashings, cable anchors and other such restraints as well as rock bolts and dowels in the list of reinforcement systems.

In most situations where support or reinforcement is required, the measures to be applied must be designed for that specific site.

Support Systems

The choice of the support system or systems for a particular location depends upon the geologic conditions at the site such as the properties of the rock, the type and orientation of the discontinuities, ground water conditions, the configuration of the slope, and the size and amount of material involved.

Buttresses are used in steep terrain to support rock that shows stress or danger of falling and which cannot be removed due to inaccessibility or because its removal would undermine other material at higher elevation. Rock anchors or bolts are commonly used in conjunction with buttresses to stabilize and tie the rocks together. Brawner and Wyllie (1976) suggest that some buttresses may be built up with layers of shotcrete and wire mesh. The buttress must be designed to take the line of thrust of the load it is to support. Small volumes of material may be buttressed by dry rock packing. Buttresses may be at road level or at other locations on the slope.

Retaining walls are generally used to prevent large blocks or long zones of rock or soil from moving downslope. Anchors and/or rock bolt tie backs may be used with them to make them more resistant to movement. Such design may also be required where the working width is too narrow for a gravity wall.

Reinforcement Methods

Rock bolts are used to tie in-situ fractured rocks together to add shear and frictional resistance to the interfaces along which individual blocks would move. There are several different rock bolt designs but all are intended to be anchored at the bottom of a drilled hole and then be placed in tension by means of a nut threaded onto the free end of the bolt. The nut bears against a large washer placed over the bolt. In this "active" reinforcement system, the rock mass is placed in compression which tends to lock irregularities on the rock surfaces together causing an increase in frictional resistance to movement. Additional shear resistance is obtained from the steel bolt. Wire mesh and shotcrete or gunite are often used in conjunction with rock bolts to add structural strength to the system. As Lang (1972) points out, safety for workmen is enhanced as well. Steel cables may be used instead of the bolts where very long anchors are required.

Lang (1972) recommends that for permanent service, all bolts should be grouted. The installation and tensioning of grouted bolts is the same as for ungrouted bolts and the grouting is done after installation. Grouting should be done without releasing the tension on the bolts. Grouting can be done some time after installation if necessary.

Bolt-Lock, Inc., a subsidiary of Atlas Powder Company, produces a product called Res-Lock in cartridge form. Two separated components are punctured and mixed when installing the bolts to provide a fast setting method of anchoring the bottom of the steel.

Dowels are reinforcing rods or steel bars grouted into place to provide shear resistance to movement of rocks near the surface of a slope. The dowels should be fully grouted with portland cement or chemical grout so that reinforcement is provided before the rock moves. The grout prevents corrosion of the bolt by ground water and also supplies additional shear strength. Rock bolts may be used in the same way, without tensioning, to provide shear resistance to blocks that may move.

Dowels are used to provide shear resistance at the toe and ends of retaining walls. They are also used to anchor catch fences and nets, restraining nets and cables, cable catch walls and cantilever rock sheds. Dowels are used to anchor wire mesh in conjunction with shotcrete and to anchor buttresses and beams placed to stabilize adverse sloping blocks of rock.

Perfobolts are used in broken rock that requires artificial support throughout its length. This type of installation uses a thin metal tube perforated throughout its length which is filled with a rather thin grout. The bolt is then forced into the tube and the grout is displaced through the perforations into the surrounding broken rock, thereby providing support throughout the length of the rod. Piteau and Peckover (1978) note that it is difficult to displace the grout by hand in holes that are over 20 feet long.

Tendon and cable anchors are longer than rock bolts and are used to provide support to a larger mass of rock than bolts. The principle of reinforcement is the same as for rock bolts. They have been used to provide support at various points along retaining walls and may also be used in place of retaining walls in some locations.

Anchored beams of concrete or steel may be installed at any angle across a slope to support rock slabs. The required number of rock bolts may be reduced in this manner.

Anchored cable nets are used to restrain large rocks up to eight feet in diameter. They are made from individual cables that form a restraining net around the rock and the individual cables are then gathered and connected to the main restraining cable on either side. The main cable is then anchored to solid rock by rock anchors. Cable nets are also used to control a mass of smaller rock in a similar manner. Beam and cable walls have been used on slopes up to about 60 feet high to prevent rocks from falling from the face. The beams, spaced approximately 10 to 20 feet apart, are leaned against the slope and anchored by setting the bottom end of the beams in concrete footings and by anchoring the tops to the face with cables. Cable nets are then attached to the beams to reinforce rocks.

Cable lashings are used to stabilize large rocks. These are usually individual rocks but may be a mass of fractured rock. Individual cables or chains are wrapped around the rock and the ends anchored to stable rock on each side. Concrete or metal beams may be used in conjunction with the lashings to spread the points of contact over a larger area.

Protection Methods

Protection methods are used to prevent moving rock from reaching the traveled way. These methods are designed to redirect rock to a safe area, to stop and store rocks above and/or at road level, or to avoid the rockfall problem area.

In order to choose the possible protection methods at any given location, the following factors must be considered:

1. The size and abundance of rocks involved,
2. the geometry of the slope,
3. the motion characteristics of the rock,
4. the geologic features of the slope that may influence a decision, and
5. available width at the base of the rockfall zone.

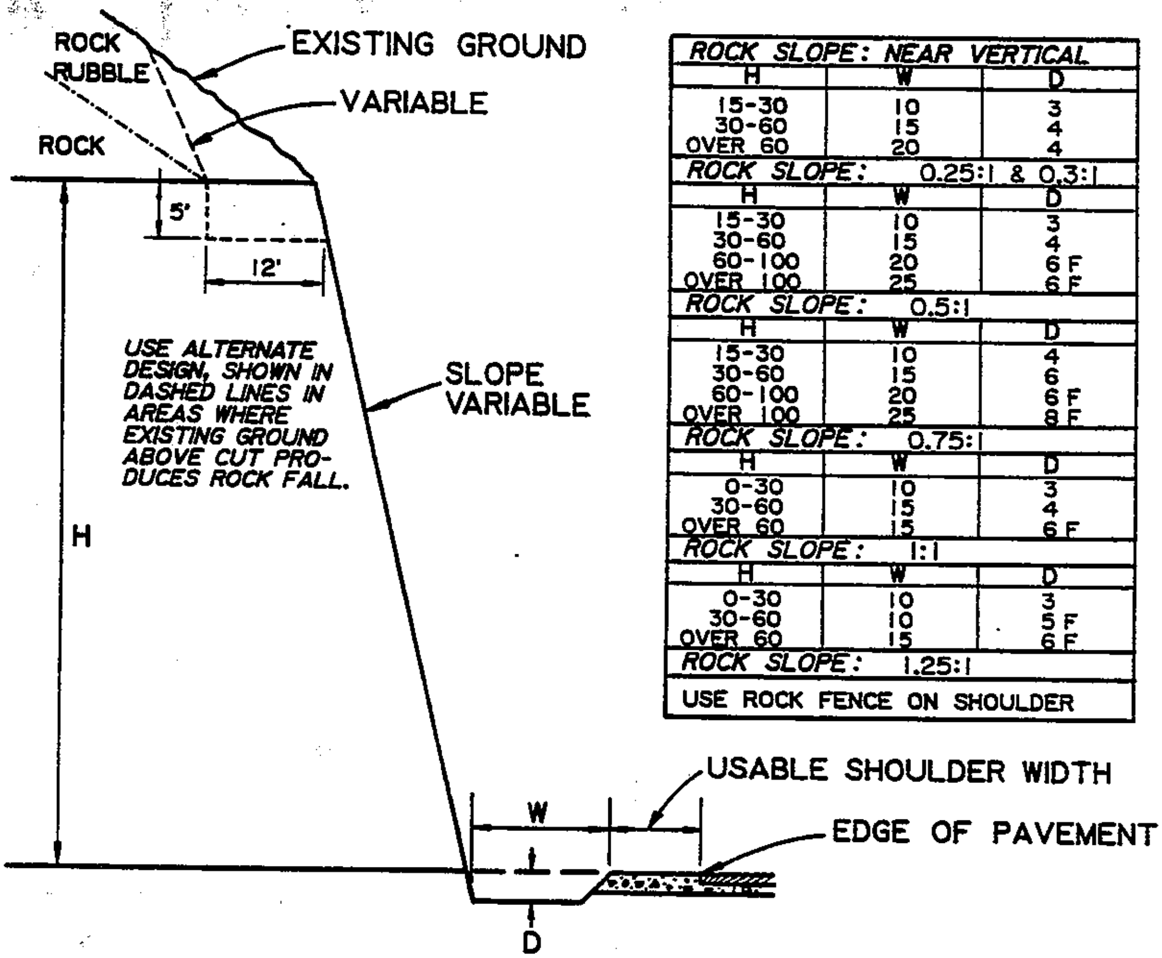
All of these factors must be considered together because one may influence another. For instance, large rocks require more positive means of protection than small rocks; the abundance of rocks influences the amount of storage required; the geometry of the slope influences the motion characteristics of the rock; the motion characteristics of the rock determine the distance from the face in which moving rocks will be found; the geologic features of the slope determine the future severity of the rockfall, influences the motion characteristics, may determine the size of rock that may fall and contains information on ground water and surface water that may play a part in decisions; and the available width at the base of the zone, which commonly is at road level, may affect the cost of the project and thereby influence the choice of mitigation measures.

Relocation

Relocation of the road should be considered for locations where rocks impact onto the traveled way and where support or reinforcement methods cannot be used. A catchment ditch and/or a barrier, in conjunction with a shift in alignment, is often a very satisfactory solution to the problem. If the road is shifted out and a ditch is not required, it is advisable to scarify the previous traveled way to reduce the height of bounce. Road realignment may be obtained by the construction of a sidehill viaduct or bin wall. In extreme situations, total surface realignment of the road or placement of the road in a tunnel may be the only alternatives.

Catchment Ditch

A catchment ditch at road level is considered to be the best way to control large falling rock. According to studies by Ritchie (1963), a ditch width of 25 feet having a depth of 8 feet and wire mesh fence along the top of the ditch next to the traffic is sufficient to control most rocks for most slopes (see Figure 7). He does mention, however, that at one location having a cut 90 to 130 feet high, the fallout zones were 19 and 34 feet in width. The



H	W	D
ROCK SLOPE: NEAR VERTICAL		
15-30	10	3
30-60	15	4
OVER 60	20	4
ROCK SLOPE: 0.25:1 & 0.3:1		
15-30	10	3
30-60	15	4
60-100	20	6 F
OVER 100	25	6 F
ROCK SLOPE: 0.5:1		
15-30	10	4
30-60	15	6
60-100	20	6 F
OVER 100	25	8 F
ROCK SLOPE: 0.75:1		
0-30	10	3
30-60	15	4
OVER 60	15	6 F
ROCK SLOPE: 1:1		
0-30	10	3
30-60	10	5 F
OVER 60	15	6 F
ROCK SLOPE: 1.25:1		
USE ROCK FENCE ON SHOULDER		

When required for slope stability, the use of benches is satisfactory; however, they do not alter the design and values shown. Ordinarily, their use will be a result of the soils study and be on the recommendation of the Materials Engineer.

Where the existing ground above the top of cut is on a slope approximating that of the cut slope, the height (H) shall include the existing slope or that portion of it that can logically be considered a part of the rock cut.

Ordinarily, guardrail shall be provided where D is greater than 3. F permits diminishing D to 4 if fence is also used.

GENERAL DESIGN CRITERIA FOR SHAPED DITCHES (After Ritchie, 1963)

Figure 7

cut was on a slope of 1/4:1. Most catchment ditches require a fence or barrier next to the highway to stop rocks that roll up the side of the ditch or that shatter when striking another rock already in the ditch. Slopes cut on 1/4:1 and 1/2:1 require wider ditches than other slopes. The adverse slope of the ditch next to the highway is most effective when it is very steep. However, the steep slope adjacent to the traveled way may be a hazard to the traveling public. Nevertheless, in rockfall areas, the greatest hazard should be given design priority. Studies have shown that loose granular material placed in the bottom of the catchment ditch absorbs energy of the impacting rock and thereby reduces rebounding motion. In areas that freeze, this material should be coarser and free-draining to prevent the ice from forming a hard surface that would nullify the purpose of the material. Mearns (1976) suggests using pea gravel. Ritchie reports that fine quarry-run spoils are just as effective as sand.

Intercepting Sloped Ditches

Sloping ditches have been constructed to intercept and guide moving rocks to catchment areas. Berms have been added to the outside edge of ditches to make them higher and more effective to control the rocks. Such ditches can be used in locations where there is a sloping interface between a source of rockfall overlying other stable material. Also, more than one ditch could be constructed to decrease the distance rocks roll before entering the ditch. Caution should be used to avoid the creation of a launching platform or rounded ditch from which rocks could travel a significant horizontal distance. Ditches should be maintained to prevent excessive rock accumulation. The construction of these ditches must not cause instability of the slope. Sloped ditches may be used on a talus slope that extends to the highway for intercepting rolling rocks.

Anchored Wire Mesh and Wire Mesh Blankets

Wire mesh may be pinned to the slope face to prevent rocks from falling, or hung loosely over a slope to guide rocks to a ditch at road level. Such methods are effective for rocks up to two or three feet in diameter (Peckover and Kerr, 1977). Gabion-type wire mesh has the advantage of being more easily repaired than chainlink mesh but chainlink mesh is very flexible in one direction.

Wire mesh that is attached to the slope may fail due to the pressure of accumulated material or movement of a large rock. Mesh that is not attached may be damaged by large rocks or accumulation of snow. Thus, it is usually not used on slopes flatter than 3/4:1 in snow country. However, Lane and Vaniker (1980) describe fencing attached to a grid of horizontal and vertical wire ropes to add strength to the installation. A fencing support cable is anchored above the top of the cut with rock dowels or rock bolts. The fencing is attached to the cable by looping the upper foot of the fencing around the support cable and then woven together with 9 gauge steel lacing wire. The length of wire may be necessarily shortened to 10 feet or less because of its stiffness. Adjacent vertical strips may be connected with steel hog rings. A steel ring placed between steel plates and held in place with rock dowels allows attachment of the horizontal and vertical cables to the bolts. All hardware is galvanized to resist rusting. The bottom edge of the fencing may be allowed to hang freely a few feet above the bottom of the ditch line to allow rocks to drop out and to allow rock removal equipment to

Monitoring

The downslope movement of rock can be monitored in a variety of ways that includes measurement between two points, surveying, automatically recording extensometers, and acoustic emission. These systems work well for monitoring landslides, but most rockfall happens almost instantaneously and there is practically no warning time or reaction time available. These systems might be applicable to a situation where a rock was slowly moving toward the edge of a steeper slope.

No Photo Available

Benefits

* Quick and easy to install
* Can be used until another mitigation is completed

Cautions

* Does not solve the rockfall problem
* Requires analysis of results
* Warns after the event

Cost Rating

1 - 2

that have impacted at road level before encountering the fence. Preferably, the impacted surface contains energy absorbing material and slopes steeply downward toward the toe of cut.

No space should remain between the bottom of the fence and the ground because rolling rocks can force themselves under the fence if given enough space. A small berm of any available material formed at the inside edge of the fence after cleanup is completed will assure that no space remains. The berm will also direct rolling rock up into the fence where they are more easily contained. Catch fences may require considerable maintenance in snow country where plows and snow blowers cover the fences with snow and ice and where snow avalanches cross the road.

Catch fences slow rocks before they arrive at the bottom of a slope provided the rock moves by rolling rather than bouncing. The slope should be relatively smooth and devoid of rocks or outcrops above the fence so that rocks will not be launched over the fence. Talus slopes are an example. Ritchie (1963) shows this slope angle to be 1-1/4:1 or flatter. The catch fence is constructed similar to that at the bottom of a slope except that the supporting posts will be set perhaps 50 feet apart to avoid being struck by rock. The fence is allowed to freely drape downslope several feet to act as a brake to the rock as they roll under the mesh. The cable can be attached to a compressive spring to absorb the shocks of the rocks. Ritchie mentions for their tests a spring taken from an old guardrail setup was used.

Catch nets are suspended across rock chutes or gullies to slow bouncing rocks before they reach the road level. Lengths of fencing are suspended from a cable stretched across the gully and cut to length to fit the cross-section at that location. The sides of the fencing are lapped and tied together with hog rings or lacing to make a continuous curtain. Care should be exercised to set the cable high enough to catch rocks that are airborne. More than one net may be used to repeatedly slow the rock in long gullies. To increase the chance of catching all rock, nets may be placed rather closely together where the gully is shallow, where rocks bounce high into the air or where they shatter. These nets are usually placed near the lower end of the gully where the rock can be stopped by a fence, barrier, ditch or combinations of these placed near the road.

Heierli (1976) describes a braking system developed to absorb energy of large rocks that impact catch nets and fences constructed with cables. The brake system diminishes the maximum shear force imposed on the supports and cable elements of the system. It consists of a cable loop furnished with a friction brake that can be set for a given shear value before being placed in the field.

Catch Walls

Catch walls are constructed to stop large rolling or bouncing rocks, to gain extra distance between the slope and the top of the wall or to provide additional storage for rocks to reduce the frequency of removal operations. Space is usually limited for such installations. However, provision should be made to allow rock removal since too much accumulation of material will reduce efficiency of the wall.

Catch walls have been constructed of reinforced concrete, gabions, rails and ties, posts and cables, I-beams and timbers and posts and timbers. Concrete walls and posts can be tied to rock with cables attached to rock bolts or the posts can be braced from the roadway side. Anchors should be placed to allow cleanup equipment to operate.

Concrete walls may be cast in place or precast in sections and joined together at the site. The inside face of the wall should be vertical to prevent rocks from bouncing over upon striking the wall. Because rigid walls do not easily absorb energy without being damaged, measures should be taken to protect them from direct impact of large rocks. The wall should be set out from the slope as far as possible to allow rocks to impact into the ditch area prior to striking the wall. The bottom section of a rigid wall may be partially protected from impact by a berm of rocks faced with gravel or by gabions. The entire rigid wall can be protected to some extent by facing the inside with heavy timbers. A wire fence may be mounted on top of catch walls to stop small rocks that are airborne.

MITIGATION MEASURES USED IN OTHER STATES

Inquiries were sent to 15 State Transportation Departments requesting information about the types of mitigation measures used in their state. Extensive information was obtained from 14 of the states, with the 15th indicating that they had no rockfall problem. Additional information was obtained from some of these states by telephone.

Most states indicated that each rockfall problem was treated individually. Some treatments were very innovative. Figure 8 summarizes the responses obtained from the correspondence. Twenty-six methods were mentioned although some are variations of the same type. Six methods mentioned by half or more of the states are:

1. Shaped and/or widened ditch at grade (10)
2. Draped wire mesh (9)
3. Chainlink (or wire) fence at grade (8)
4. Scale or trim slopes (8)
5. Controlled blasting (7)
6. Rock bolts (7)

New Mexico indicated they used 12 of the listed methods, with Oregon including 11, and Alaska and Nevada both indicating the use of 10 methods. No state listed the use of structural methods such as tunnels or rock sheds to solve rockfall problems.

ROCK SLOPE MITIGATION METHODS USED BY SELECTED STATES

STATES	FLATTEN SLOPE	SCALE OR TRIM	SKEWED, MULTIPLE ANGLE SLOPES	SLOPE DESIGNED TO GEOLOGY	CONTROLLED BLASTING	SUB-SURFACE DRAINAGE	ROCKBOLT OR DOWELS	SHOTCRETE OR GUNNITE	ANCHORED WIRE MESH	CABLE LASHING	RETAINING WALL	SLOPE AT MAX. STEEPNESS	HIGHWAY RELOCATION	BENCH	STANDARD GUARD RAIL	METAL BARRIER	PCC JERSEY BARRIER	GABION	EARTH BERM	INTERCEPTING SLOPE DITCH	SHAPED DITCH AT GRADE	"TELEPHONE POLE" RETAINER	DRAPED WIRE MESH	AGGREGATE IN DITCH LINE	METAL BIN WALL	WIRE MESH FENCE
ALASKA		X		X	X	X	X					X						X			X		X			
ARIZONA	X	X									X		X	X												X
COLORADO		X					X	X	X					X							X		X		X	
HAWAII					X																		X			X
IDAHO		X			X												X				X		X			X
MONTANA	X	X											X			X	X									
NEVADA	X	X					X			X				X	X		X				X		X			X
N.HAMPSHIRE	X	X					X		X						X					X	X			X		
N. MEXICO	X		X		X		X	X	X								X	X			X	X	X			X
OREGON	X						X	X	X					X		X	X		X		X		X			X
UTAH		X										X		X							X		X			X
VERMONT				X	X		X				X															
WASHINGTON					X			X	X						X			X			X		X			X
WYOMING					X		X	X	X												X					

NOTE: CHART PREPARED FROM THE RESPONSES SENT TO CALTRANS FROM OTHER STATES, OTHER METHODS MAY ALSO BE USED BY LISTED STATES. COMBINATIONS OF MITIGATION MEASURES ARE ALSO USED.

MITIGATION OF ROCKFALL IN OTHER COUNTRIES

Information was obtained about rockfall mitigation measures that are used by the British Columbia Ministry of Transportation and Highways; the Canadian Pacific Railroad; the Canadian National Railroad; the Department of Public Works, State of Vaud, Switzerland; and by the Laboratoire Central des Ponts et Chaussees, France. In addition to the methods listed in correspondence from the states, these sources include other solutions to rockfall problems. They are:

1. Tunnels to avoid rockfall areas
2. Rock sheds to carry rock over the route
3. Concrete buttresses to support overhanging rock masses
4. Catch fences across natural slopes and gullies
5. Electric fence warning devices
6. Planting of glacial slopes to reduce erosion of fines from around boulders.

Both of the Canadian railroads and the British Columbia Ministry of Transportation and Highways have developed a comprehensive program for solving rockfall problems. In general, this involves setting priorities for the rockfall sites and budgeting repair money accordingly. The Canadian National Railroad spent about 1.5 million dollars per year between 1972 and 1982 on the mitigation of rockfall. They indicate they are very pleased with the results and have significantly increased safety and reliability along their main line (W. E. Jubien, letter).

ROCKFALL IN CALIFORNIA

This study was initiated because rocks do fall and roll onto highways in California. Many thousands of man-hours are spent cleaning rocks from the road and in repairing the facilities that are used to lessen the amount of rock on the roadway. Rocks have caused damage and injury or death to both the traveling public and to Caltrans maintenance personnel.

Several claims are filed against Caltrans every year that are based on damages resulting from rockfall.

One purpose of this study was to determine the extent of the rockfall problem in California and to catalogue the mitigation measures that have been used. Meetings were held with district maintenance and materials personnel to explain our research project and to request their assistance. Copies of the research proposal and a questionnaire were distributed to indicate the scope of the project. The districts were requested to provide a list of locations or zones where rockfall occurs. After receipt of these lists, tentative study sites were chosen. Highway photo log films were viewed to help make these choices.

Field reviews were then made, photographs taken, and sites were selected for further study. An effort was made to include a variety of rockfall conditions and different mitigation measures.

Ninety-two sites throughout the state were studied in detail.

The extent of areas that were reported to have rockfall is shown on the map sheet on page 80. About 3000 miles of highway in California are affected.

In order to obtain site data, a two-part questionnaire was prepared. A copy of the questionnaire is shown in Appendix B.

The first section of the questionnaire, to be filled out by maintenance personnel, was designed to obtain information relating to location, causes and frequency of rockfall, rock travel, mitigation method, and costs relating to maintenance requirements.

The second section was directed toward the physical relationship between the mitigation measures and the slope: geological features, physical properties of the rock, topography, vegetation and the road geometry. Transportation Laboratory (TransLab) personnel completed this section.

Analysis of Data

Eighty-eight items from each questionnaire were entered into a computerized data retrieval system. This system is described in Appendix C.

The data collected from the questionnaires were analyzed to develop conclusions regarding mitigation measure effectiveness and man-hours spent for maintenance. Mitigation measure is defined as the measure or combination of measures that are used at a given location. The effectiveness of the mitigation measure was given by maintenance personnel familiar with the site. The maintenance man-hours for mitigation repair per year include both maintenance and inspection time and were obtained from maintenance personnel.

Figure 9 shows the reported effectiveness of the 92 sites.

Most mitigation measures are fairly effective with 45 percent reported at least 80 percent effective and only 13 percent less than 50 percent effective. The average mitigation measure effectiveness is 70 percent.

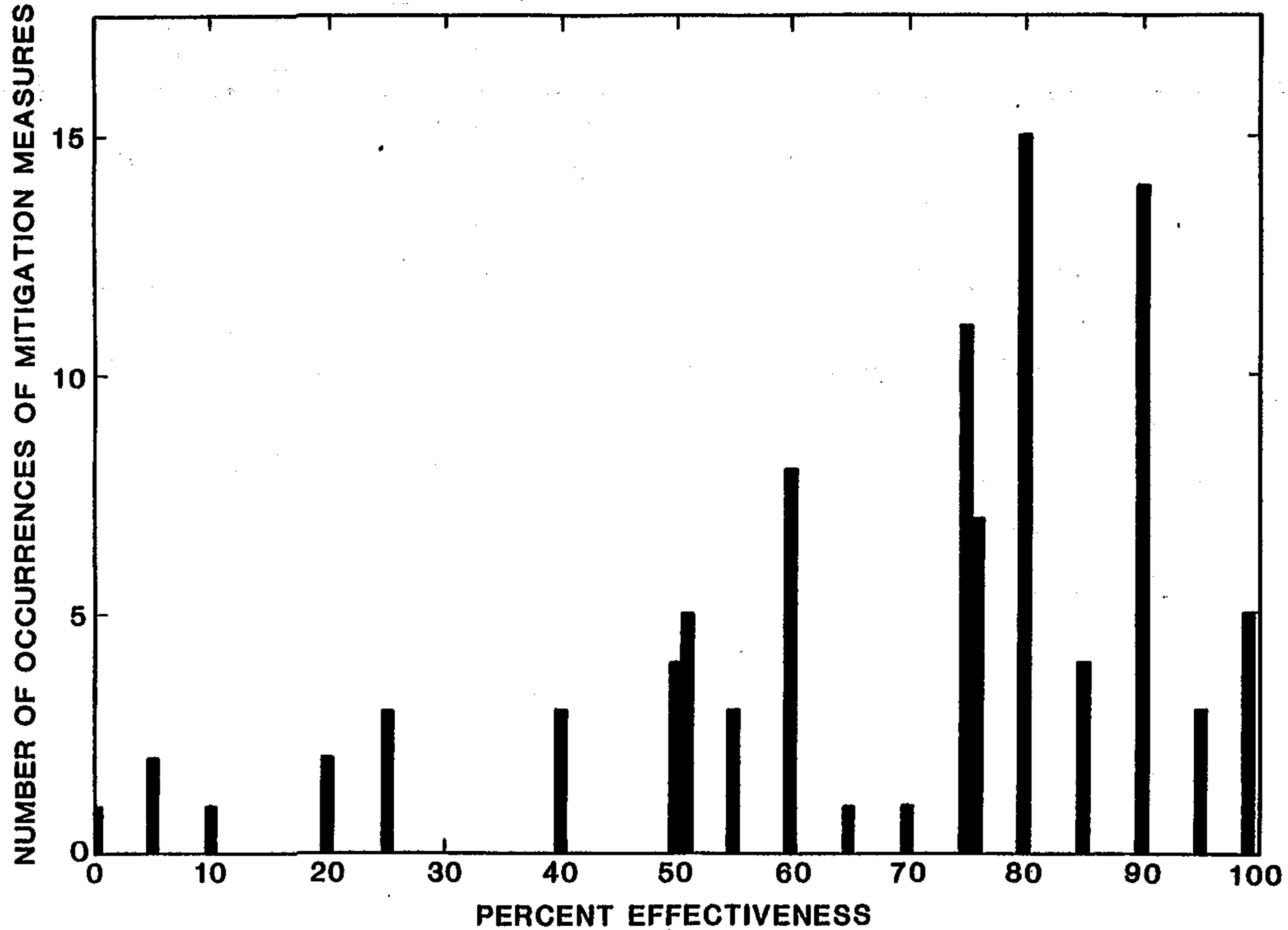
Figure 10 shows the man-hours per year spent for maintenance plotted against the number of sites.

The distribution of the number of sites versus man-hours for maintenance shows that 71 percent of the mitigation measures used 100 man-hours or less per year for maintenance and 48 percent of the measures used 40 hours or less. The average number of man-hours spent per year for maintenance of a mitigtaion measure is 92 hours.

In California, almost 50 percent of all treatments for rockfall involved more than one mitigation measure.

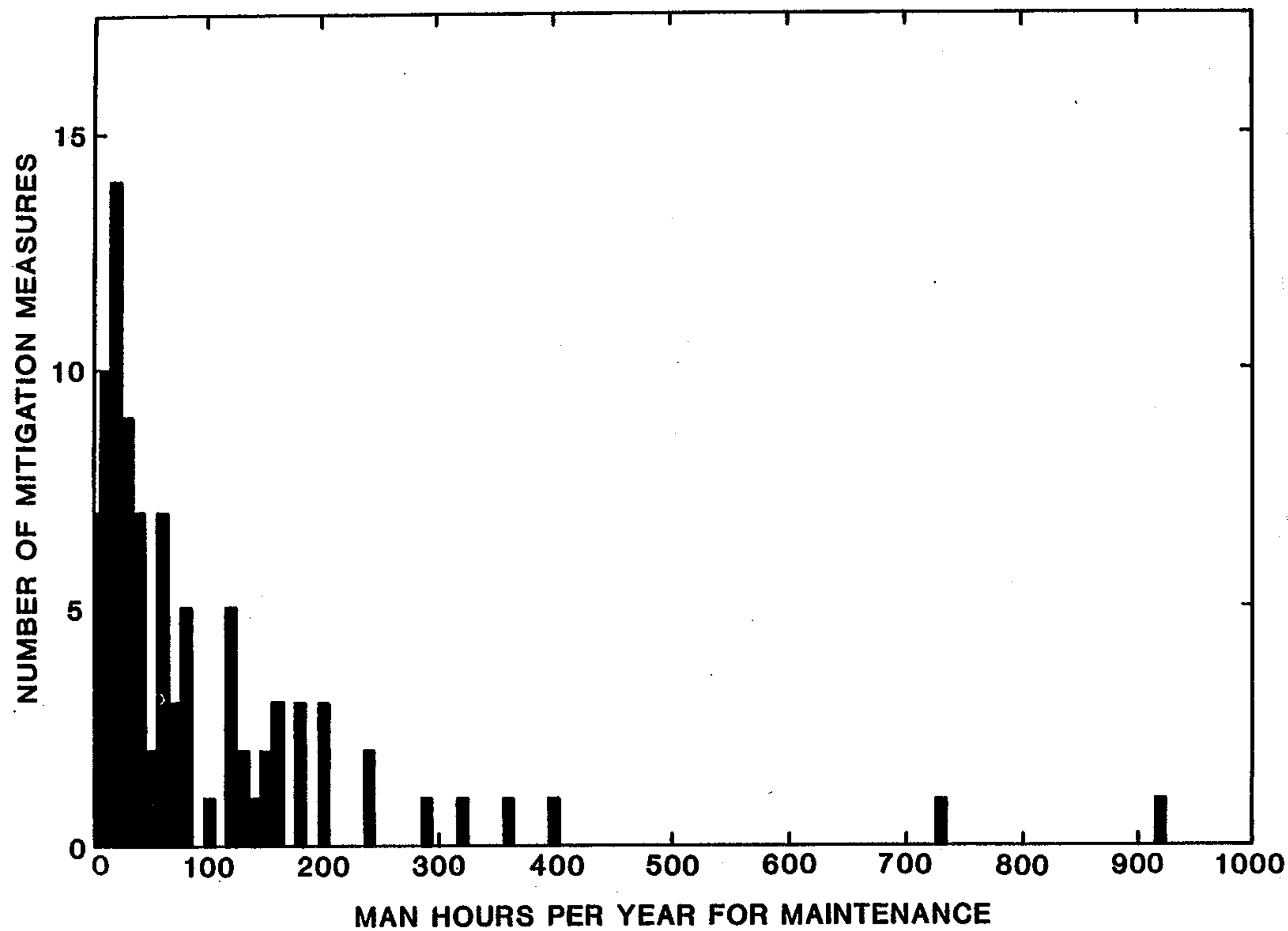
Widening at grade is used more than any other measure. Of the 92 sites reviewed, 61 had widening with or without other measures and 20 had widening only. Effectiveness ranges from 5 to 90 percent with the average being 88 percent.

Fences were the second most widely used method. Of the 92 sites reviewed, 43 had fences with or without other methods and 11 had fences only. Fencing has a range of effectiveness from 15 percent to 99 percent with an average of 74 percent. A breakdown of effectiveness for fences with and without other measure(s) is shown below.



THIS GRAPH SHOWS THE NUMBER OF MITIGATION MEASURES REVIEWED VERSUS PERCENT EFFECTIVENESS

Figure 9



NUMBER OF MITIGATION MEASURES VERSUS THE MAN-HOURS SPENT PER YEAR

Figure 10

Mitigation Measure	Range of Effectiveness	Average Effectiveness
Fence Only	60% to 90%	77%
Fence with widening at grade	25% to 90%	73%
Fence with benched slope	51% to 90%	79%
Fence with ditch and berm	80% to 85%	82%
Fence with benched slope and widening at grade	75% to 90%	81%
Fence with draped wire mesh and widening at grade	75%	75%

All the measures involving fences were checked to see if they meet Ritchie's(1963) criteria for distance from toe of the slope to fence. Only 10 of the fences reviewed meet Ritchie's criteria. For those 10, the range of effectiveness is 75 percent to 95 percent and the average effectiveness is 83 percent. The average effectiveness for fences not meeting Richie's criteria is 72 percent.

Three factors reduce the effectiveness of the fences that meet Ritchie's criteria. For one thing, some of the fences have a gap of six inches or more between the bottom of the fence and the ground (see Figure 12). This gap facilitates cleanup operations but obviously allows rock to roll under the fence. The gap may be created by cleanup operations or the fence may be installed with the gap. A second problem related to fences is that rolling rocks larger than two feet in diameter cause serious damage to the fence and may render it ineffective (see Figure 11). The third problem recorded for these fences was damage from snow or snow removal operations.

Figure 11. Fence that has reduced effectiveness caused by large rocks.

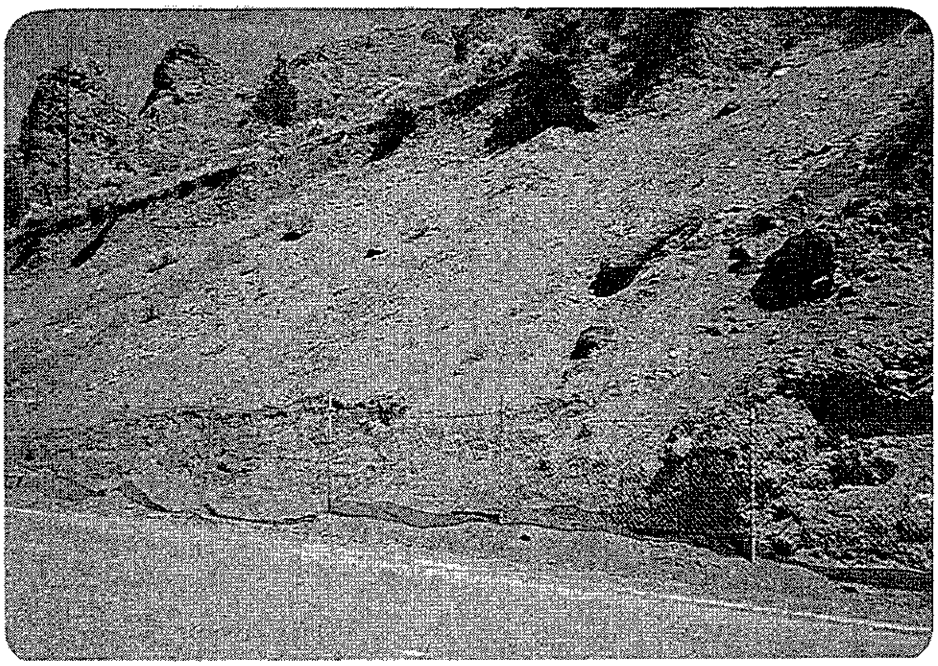


Figure 12. Large gap below bottom of the fence.

Other mitigation methods used were ditches, draped wire mesh, benching of the slope, rock walls, catch fences, overhanging fences, berms, K rail, and scaling. Each of these types were used as a single method at no more than two sites each. Most of these measures were used in combination with one or more other methods. The effectiveness for exclusive usage cases was reported as follows:

Mitigation Measure	Effectiveness
Ditches	50% and 80%
Benches	76% and 90%
Rock Walls	80% and 90%
Catch Fencing	76%
Berms	75% and 85%
K Rail	90%
Scaling	51% and 60%

Examination of the questionnaires for these sites suggests that the effectiveness of some of these measures could be improved by proper design of the feature and use of Ritchie's criteria. The rock wall and K rail sites reviewed are adequately designed. Improvement in design cannot be applied to the scaling sites. Scaling at these sites is not an effective or long-term mitigation because differential erosion develops rockfall rapidly.

In further examining the data contained in the questionnaires, the reported percent effectiveness for a site was plotted against the following information:

1. Average Annual Precipitation
2. Cut Slope Evenness
3. Frequency of Mitigation Repairs per Year
4. Minimum Width at Grade

5. Distance from Toe to Fence
6. Maximum Slope Height
7. Rock Type

Very few conclusions or correlations can be drawn from these plots. However, Plots 4 and 5 do show the benefit of widening at grade. The plots are contained in Appendix D.

Man-hours spent per year for inspection and maintenance was plotted against the following information.

8. Percent Effectiveness of All Mitigation Measures
9. Percent Effectiveness of All Mitigation Measures Using Fences
10. Percent Effectiveness of All Mitigation Measures Using Draped Mesh
11. Percent Effectiveness of All Mitigation Measures Using Benched Slopes
12. Percent Effectiveness of all Mitigation Measures That Include: K rail, Scaling, Overhanging Fences, Berms, and Rock Walls
13. Maximum Slope Height
14. Cut Slope Evenness
15. Average Annual Precipitation
16. Rock Type
17. Frequency of Repairs to Mitigation per year
18. Percent Effectiveness of Ditch and Ditch Widening
19. Minimum Width at Grade
20. Percent Effectiveness of Widening
21. Minimum Distance from Toe of Slope to Fence

There is very little correlation in these plots and they are included in Appendix D.

Induced Rockfall

The effectiveness of a mitigation measure included in this study was reported as a subjective opinion of maintenance personnel who were familiar with it. It became apparent from examining the questionnaires that additional information about how some mitigation measures worked would be useful. As a result, an "induced rockfall" program was developed.

Eleven sites were selected at which rocks would be rolled down the slopes while the action was observed and photographed. Slope angles ranged from 1-1/2:1 to 1/2:1. The width from toe of slope varied from 6 feet to 42 feet. Three berms and nine fences were located at various spacings from the toe of slope at the sites. The physical characteristics of the site were recorded (see Figure 13) and the data for each rock rolled down the slope were entered in the test data sheets (see Figure 14). Maintenance personnel provided traffic control and cleanup and Headquarters Photography took motion pictures of each event. The rock rolling could be observed on film in slow motion.

The physical characteristics of each site are represented by a typical cross-section. The results of the rock rolling are listed below the cross-section followed by comments about performance.

INDUCED ROCKFALL DATA SHEET

DATE	______
LOCATION	______
REVIEWED BY	______
WEATHER CONDITIONS	______
SLOPE HEIGHT	______ FT.
SLOPE ANGLE	______ DEG.
WIDTH FROM TOE OF SLOPE TO FENCE	______ FT.
WIDTH FROM TOE TO EDGE OF TRAVELLED WAY	______ FT.
WIDTH OF PAVED SHOULDER	______ FT.
WIDTH OF UNPAVED SHOULDER	______ FT.
REVERSE SLOPE AT GRADE	______ DEG.
FENCE HEIGHT	______
VERTICAL CLEARANCE UNDER FENCE	______ IN.
FENCE REINFORCEMENT	______ YES ______ NO
OVERALL EFFECTIVENESS	______ 0-25%
	______ 26-50%
	______ 51-75%
	______ 76-100%

DESCRIPTION OF SLOPE CONDITIONS:

DESCRIPTION OF FENCE:

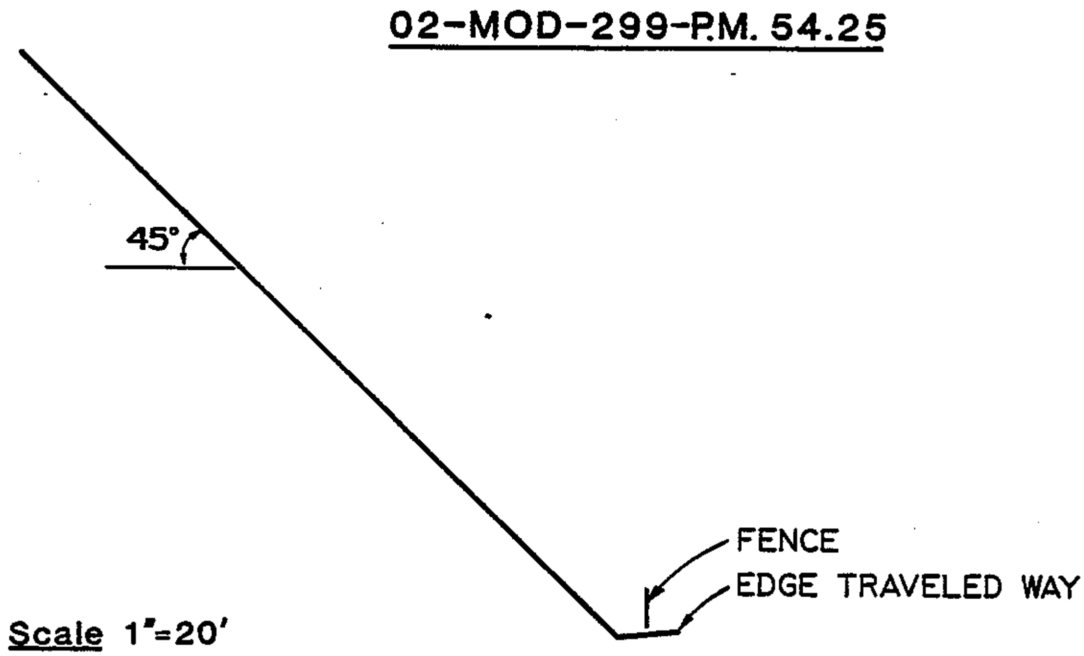
Figure 13

TEST DATA SHEET

ROCK SIZE	________ FT.
ROCK SHAPE AND ROUNDNESS	________
MODE OF TRAVEL	________ ROLL
	________ BOUNCE
	________ SLIDE
	________ FREEFALL
LENGTH OF ROLL IN TIME, t	________ FT.
TIME	________ SEC.
VELOCITY	________ FT./SEC
DISTANCE PAST TOE OF SLOPE	________ FT.
DISTANCE PAST EDGE OF TRAVELLED WAY	________ FT.
HEIGHT OF IMPACT IN THE FENCE PLANE	________ IN.
ROCK STOPPED BY FENCE	___ YES ___ NO
ROCK UNDER FENCE	___ YES ___ NO
ROCK OVER FENCE	___ YES ___ NO
FENCE DAMAGED BY ROCK	___ YES ___ NO

COMMENTS:

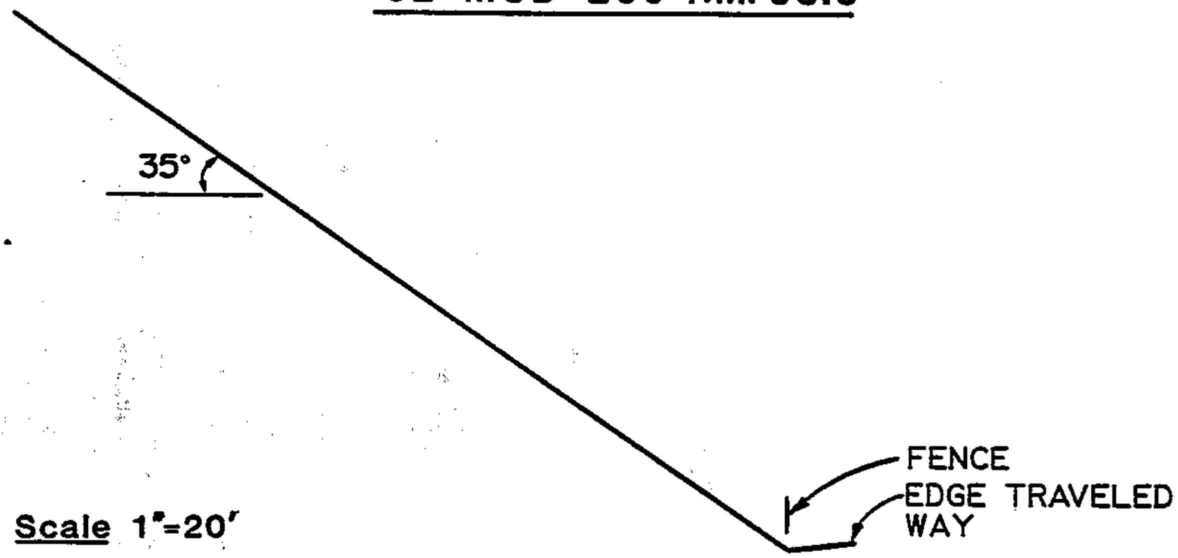
Figure 14



Rocks rolled - 21
Rocks reaching traveled way - 16
Rocks over fence - 7
Rocks under fence - 12

Comments - The bottom of the fence is 15 inches above the ground which allows many rocks to roll under it. Fence is too close to toe of slope which allows rocks to free-fall over it. Effectiveness could be improved by eliminating gap at bottom of fence. There is insufficient distance between toe of slope and edge of traveled way to prevent all rocks from going over the fence. Slope flattening to 1-1/2:1 could prevent rock from going over the fence.

02-MOD-299-P.M. 55.5



Rocks rolled - 29

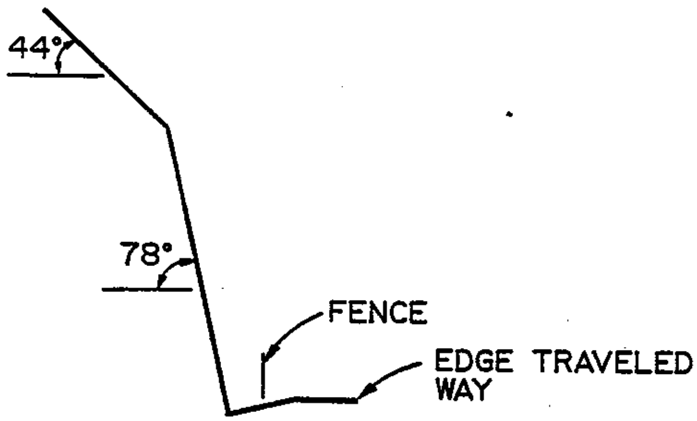
Rocks reaching traveled way - 22

Rocks over fence - 0

Rocks under fence - 27

Comments - The bottom of the fence is 4 to 12 inches above the ground which allows most rocks to roll under the fence. Installation could be totally effective if clearance were blocked.

02-PLU-70 PM 61.3



Scale 1"=20'

Rocks rolled - 10

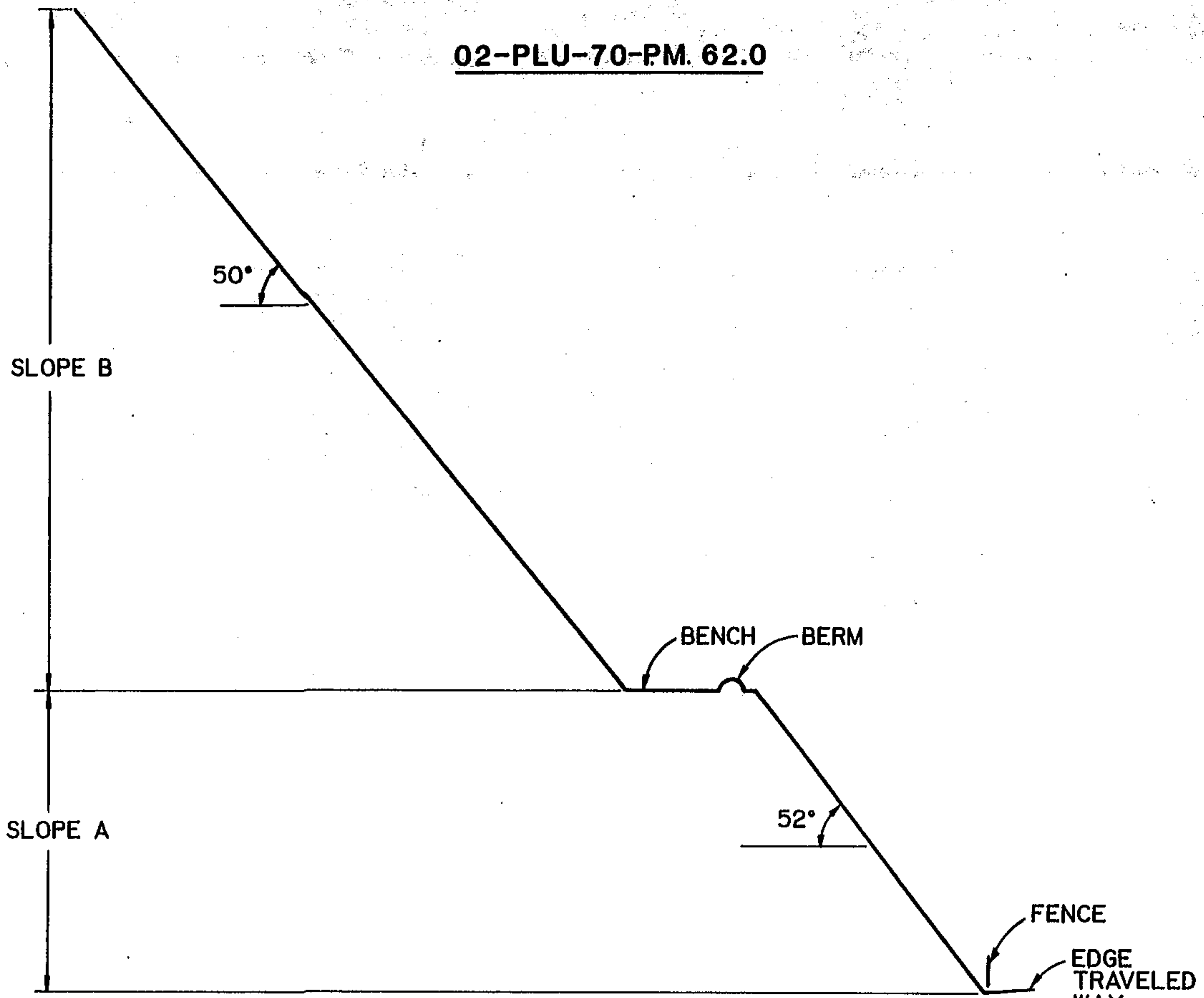
Rocks reaching traveled way - 1

Rocks over fence - 9

Rocks under fence - 0

Comments - Widening at grade is effective in keeping rocks off the traveled way even though the width is 1.5 feet short of the Ritchie criteria. The fence is useless at this particular site.

02-PLU-70-PM. 62.0



Scale 1" = 20'

02-Plu-70-P.M. 62.0

Slope A

Rocks rolled - 25

Rocks reaching traveled way - 12

Rocks over fence - 3

Rocks under fence - 20

Comments - A one foot clearance below the fence allows most rocks to roll under fence. Rocks reaching traveled way could be reduced by eliminating the gap below the fence. There is not enough width at grade for a 4-foot high fence to prevent rocks from flying over it.

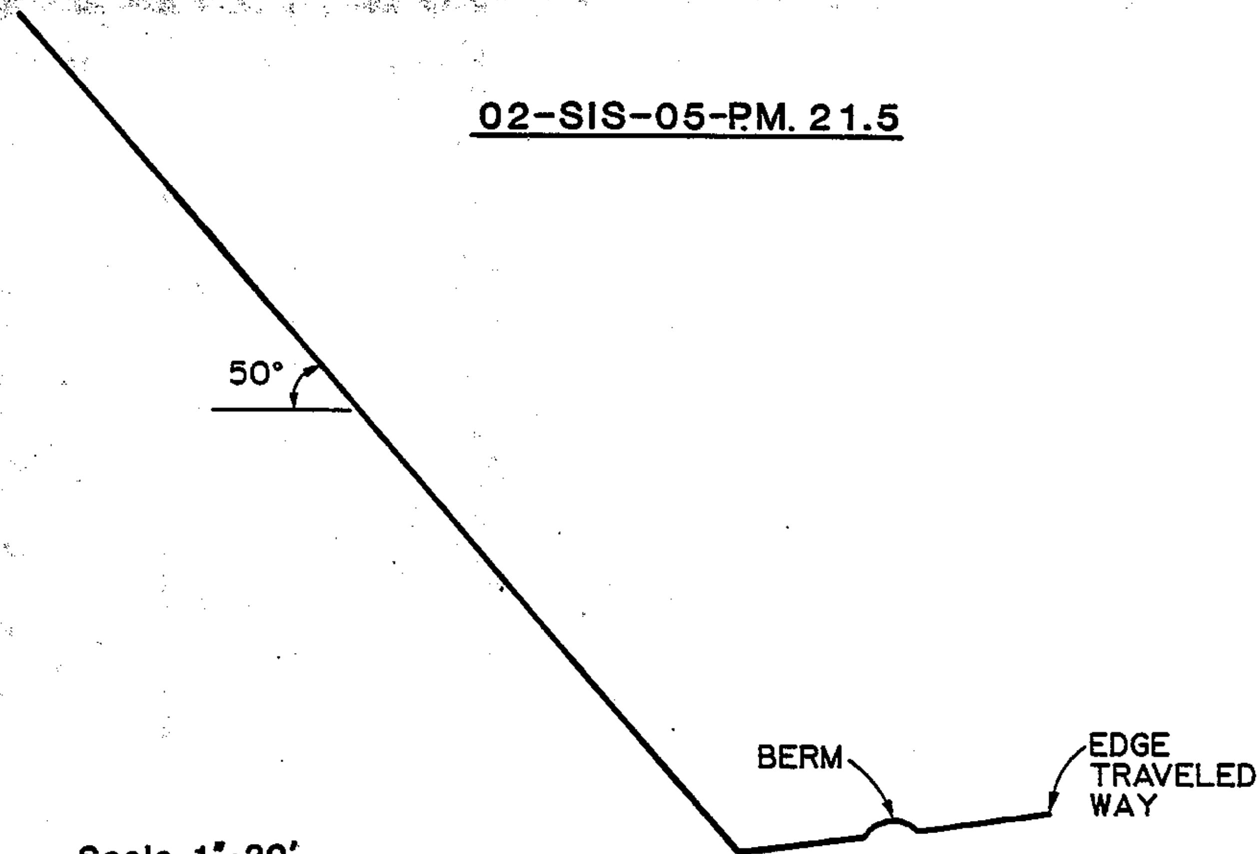
Slope B

Rocks rolled - 20

Rocks over berm - 7

Comments - Rocks could be contained on the bench by raising the height of the berm and/or placing a chainlink fence on top of the berm.

02-SIS-05-P.M. 21.5



Scale 1"=20'

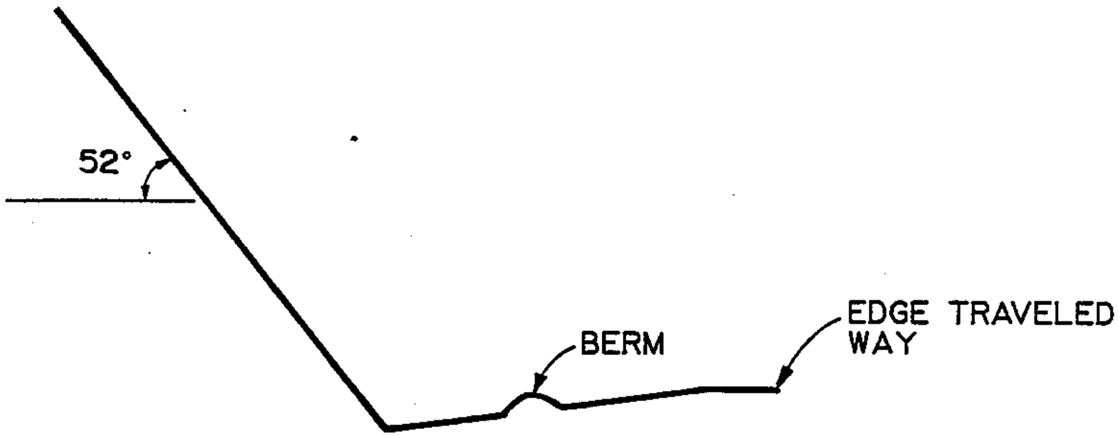
Rocks rolled - 26

Rocks reaching traveled way - 4

Rocks stopped by berm - 17

Comments - All rocks could be contained if berm height were increased to 6 feet.

02-SIS-05-P.M. 22.0

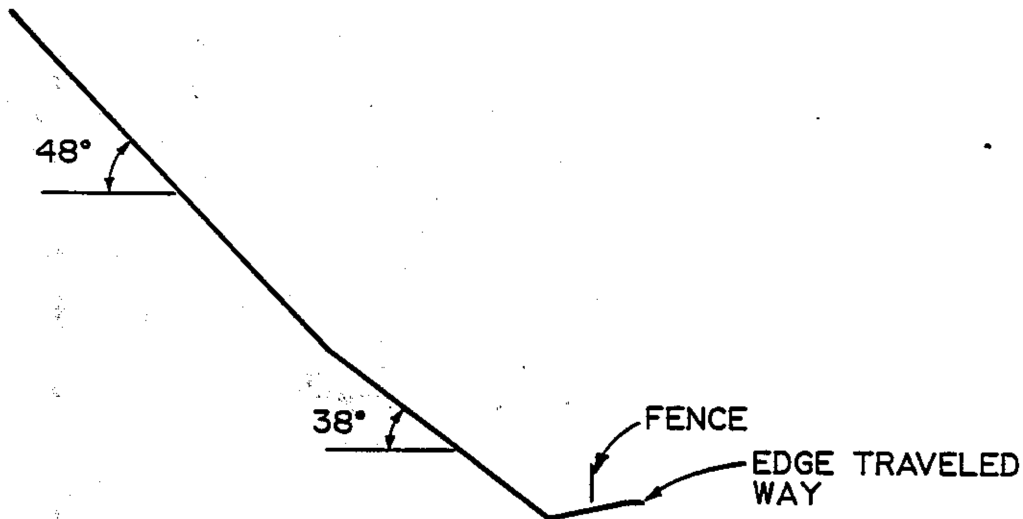


Scale 1"=20'

Rocks rolled - 13
Rocks reaching traveled way - 0
Rocks stopped by berm - 8

Comments - All rocks could be contained if berm height were increased to 4 feet. At this site, 42 feet between the toe of slope and the edge of traveled way prevents rocks from reaching the roadway. It is interesting to note that about the same percent of rocks are stopped by the berm as are stopped at P.M. 21.5 even though there is a large difference in slope height at the two sites.

03-NEV-20-P.M. 40.2

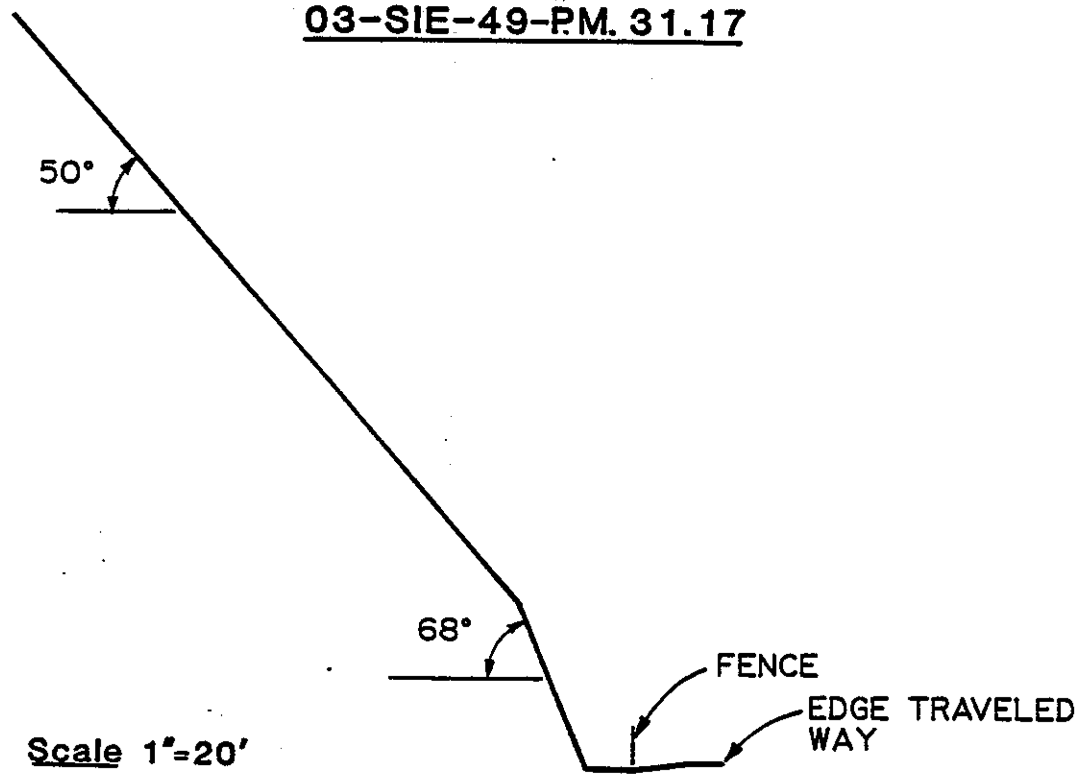


Scale 1"=20'

Rocks rolled - 35
Rocks reaching traveled way - 8
Rocks over fence - 1
Rocks under fence - 31

Comments - The bottom of the fence is 13 inches above the ground and allows most of the rocks to roll under the fence. Effectiveness of mitigation could be greatly increased by eliminating the gap below the fence.

03-SIE-49-P.M. 31.17



Rocks rolled - 10

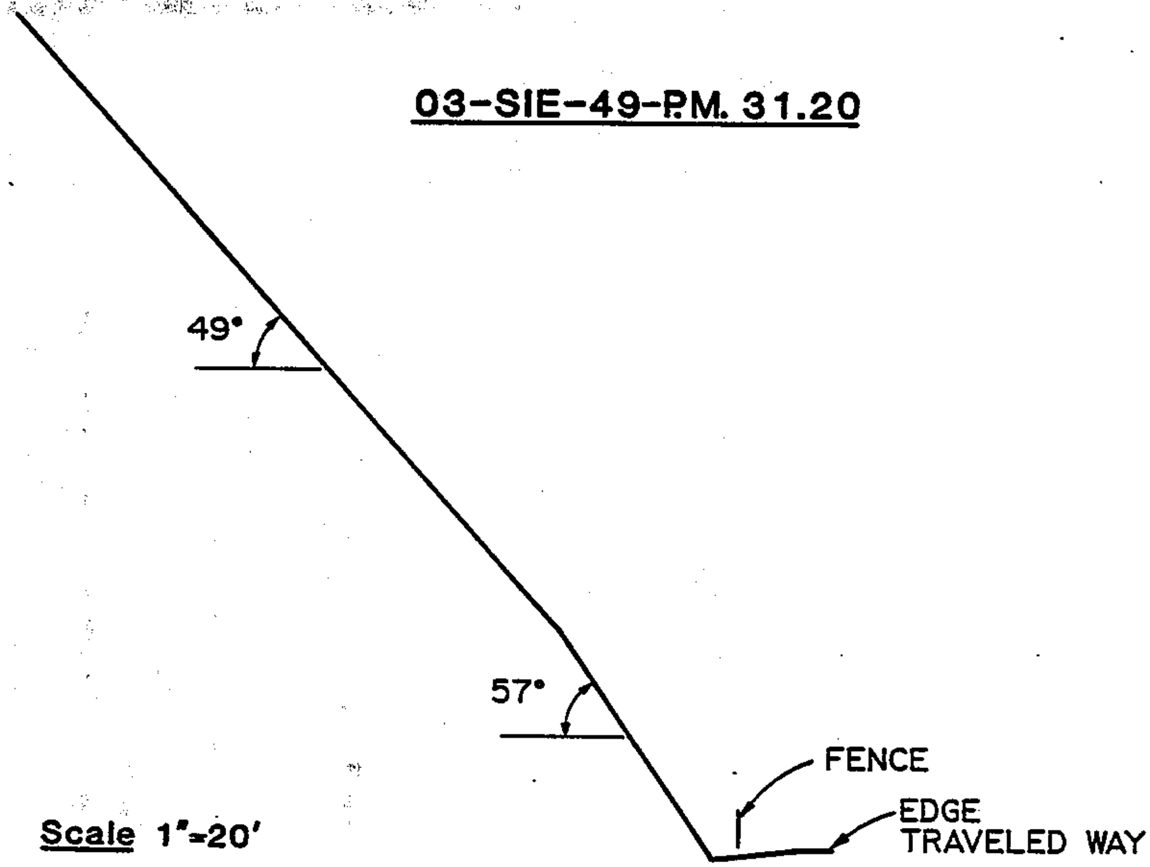
Rocks reaching traveled way - 5

Rocks over fence - 7

Rocks under fence - 2

Comments - Effectiveness of fence would be greatly improved if it were installed at least 10 feet from toe of slope.

03-SIE-49-P.M. 31.20



Rocks rolled - 8

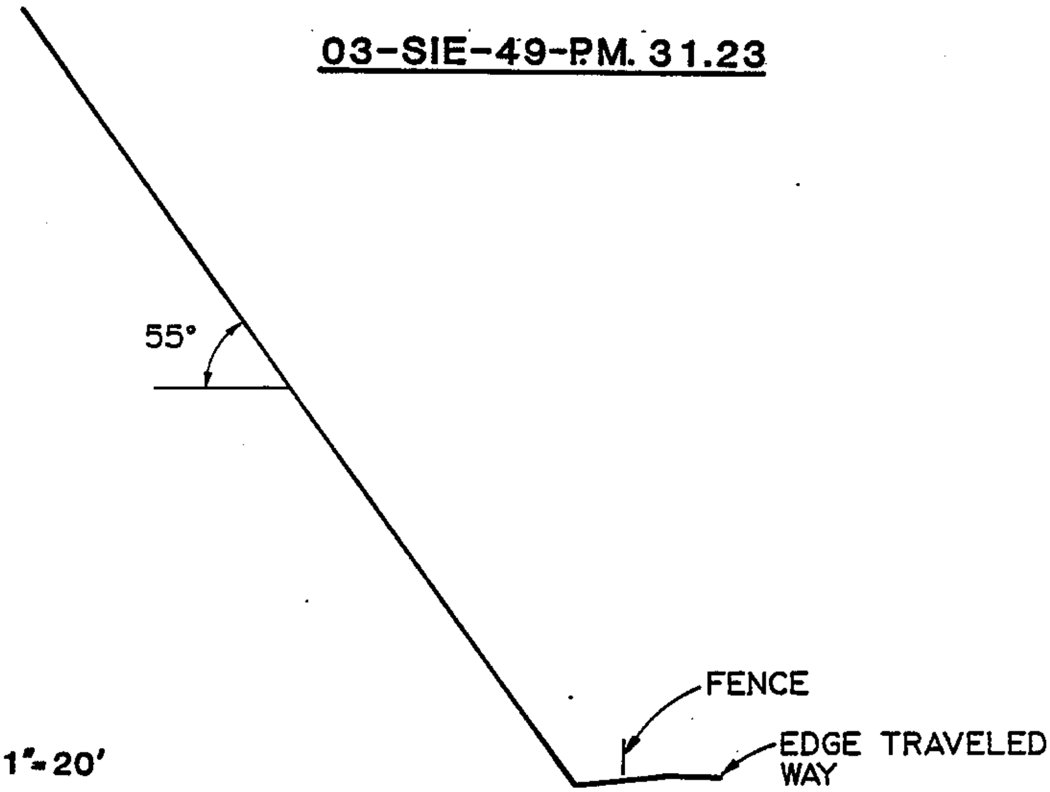
Rocks reaching traveled way - 2

Rocks over fence - 2

Rocks under fence - 4

Comments - The rocks that reached the traveled way went over the fence. Rocks going under the fence were effectively slowed. Clearance below fence is four inches. Effectiveness of mitigation could be greatly improved by moving fence at least 10 feet from toe of slope.

03-SIE-49-P.M. 31.23



Scale 1"=20'

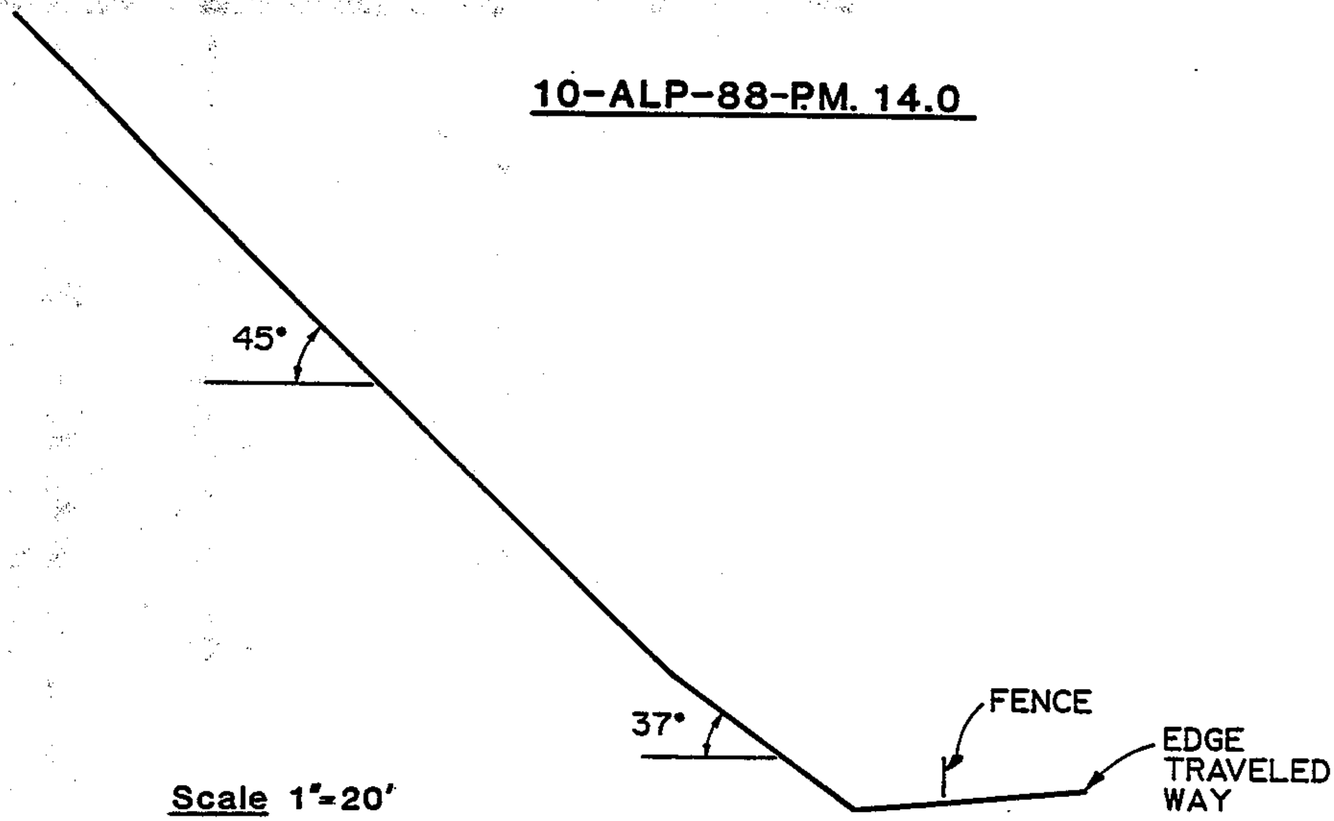
Rocks rolled - 11

Rocks reaching traveled way - 3

Rocks over fence - 0

Rocks under fence - 8

Comments - Fence is not fastened at bottom. There is a four-inch gap between bottom of fence and the ground. Effectiveness of mitigation could be improved by fastening the bottom of the fence.



Rocks rolled - 15

Rocks reaching traveled way - 1

Rocks over fence - 1

Rocks under fence - 4

Comments - Bottom of fence is not fastened. There is a two-inch gap between bottom of fence and the ground. Effectiveness of mitigation could be improved by fastening the bottom of the fence. Installing the fence further from toe of slope would probably make the mitigation completely effective.

The information obtained by rolling rocks at these sites shows that the efficiency of wire mesh fences used for rockfall mitigation could be greatly improved by 1) eliminating the gap at the bottom of the fence and 2) placing the fence at the proper distance from the toe of slope. The efficiency of berms could be improved by 1) using the proper height of berm and 2) placing the berm at the proper distance from the toe of slope.

A SYSTEMATIC ROCKFALL PROGRAM

The most direct way of minimizing rockfall is to use adequate design criteria (Ritchie, 1963) and proper construction techniques (such as controlled blasting) in the design and construction of new slopes. However, California has at least 3000 miles of highway where rockfall already occurs. Therefore, a program designed to mitigate these problems is needed. The locations are too numerous and the total costs of mitigation are too high for this to be accomplished in a short time. Thus, an ongoing program in which the sites are assigned a priority should be developed. Decisions made using such a program should provide a legal defense against charges of negligence (Peckover and Kerr, 1977).

Several types of information should be considered in assigning a priority to a rockfall site. These include:

1. Maintenance costs - This includes removing rock from the roadway and the patrols needed to observe the area.

2. Degree of risk - This may be a subjective evaluation, but should include the frequency of fall and accidents at the site.

3. Estimated cost of mitigation - Some sites can be improved for little cost while others would require extensive and expensive measures. Mitigation method can be chosen by using Appendix A. Relative costs have been assigned to the mitigation measures listed in Appendix A.

4. Potential benefit from the repairs - Some repairs will provide greater benefits than others. For example, the repair of an isolated rockfall site could eliminate the need for part of the rock patrol. This would not be the case if the repaired site were located between two other sites.

5. Importance of the route - This should include the average daily traffic and the problems caused by blocking a lane for cleanup as well as the availability of detours if needed.

The aforementioned factors are interrelated but can provide the basis for a setting of priorities. The following system is provided only as a guide to developing a method of assigning priorities. A field evaluation is needed to determine whether this method is effective. The factors may need to be adjusted for relative importance.

Priority chart for Rockfall Sites

		Rating
a.	Maintenance Costs	____
b.	Degree of Risk	____
c.	Repair Cost	____
d.	Benefit	____
e.	Importance of Route	____
		Total Points

$$\frac{\text{Total Points}}{5} = \text{Priority}$$

1. Assign a rating of 1 through 5 to factors a, b, d, e.
2. Obtain factor c from Appendix A.
3. Add the rating points
4. Divide by 5 to obtain the priority

The initial evaluation of sites can best be accomplished by using an interdisciplinary team that includes an engineering geologist, a representative from maintenance, and a representative from project development. Periodic reevaluations will be needed because conditions along a route will change. Overall responsibility for the program could logically be assigned to maintenance because they are currently dealing with rockfall.

STATE ROUTES WHERE ROCKFALL OCCURS

REFERENCES

1. American Concrete Institute, "Specification for Materials, Proportioning, and Application of Shotcrete," ACI 506.2-77, 1977.

2. Brawner, C. O. and Wyllie, Duncan, "Rock Slope Stability on Railway Projects," American Railway Engineering Association, Bulletin 656, Proceedings Volume 77, pp. 449-474, January-February 1976.

3. Ervin, M. C. and Black, G. C., "Stabilization of Rock Batters Using Dowels," Australian Road Research Board, Proceedings Volume 8, pp. 16-20, 1976.

4. California Department of Natural Resources, "Earthquakes in Kern County, California, During 1952," California Department of Natural Resources, Division of Mines, Bulletin 171, 1955.

5. Fookes, P. G. and Sweeney, M., "Stabilization and Control of Local Rock Falls and Degrading Rock Slopes," Quarterly Journal of Engineering Geology, Volume 9, pp. 37-55, 1976.

6. Franklin, J. A. and Denton, P. E., "The Monitoring of Rock Slopes," Quarterly Journal of Engineering Geology, Volume 6, pp. 259-286, 1973.

7. Gedney, D. S., "Maintenance and Safety of Rock Cut Slopes," U.S. Department of Transportation/Federal Highway Administration, Highway Focus, Volume 2, No. 5, pp. 91-102, December 1976.

8. Gietz, R. H. and Zimmerman, T. V., "Project Summary Report, Rock Slope Stabilization, Washington State," U.S. Department of Transportation/Federal Highway Administration, Highway Focus, Volume 12, No. 2, pp. 97-107, April 1980.

9. Groupe d'Etudes des Falaises (GEF), "Eboulements et Chutes de Pierres sur les Routes, Methode de Cartographie," Ministere de L'Environment et du Cadre de Vie Ministere des Transports, Laboratoire Central des Points et Chaussees, Rapport de Recherche LPC N° 80, Juillet 1978.

10. Groupe d'Etudes des Falaises (GEF), "Eboulements et Chutes de Pierres sur les Routes, Recensement des Parades," Ministere de L'Environment et du Cadre de Vie Ministere des Transports, Laboratoire Central des Points et Chaussees, Rapport de Recherche LPC N° 81, Juillet 1978.

11. Heierli, W., Protection from Rock Slips and Falling Rock by Means of Steel Wire Nets," Shultz gegen Felssturz und Steinschlag mit Drahtseilnetzen (German), Schweiz. Bauztg. 94, No. 41, pp. 611-614, 5 fig., 1976.

12. Highway Research Board of the National Academy of Sciences, "Stability of Rock Slopes, 5 Reports," Highway Research Board of the National Academy of Sciences - National Research Council, Highway Research Record, Number 17, January 1963.

13. Lane, R. M. and Vanikar, S. N., "Installation of Wire Mesh Blanket to Control Rock Falls," U.S. Department of Transportation/Federal Highway Administration, Highway Focus, Volume 12, No. 2, pp. 1-11, April 1980.

14. Lang, T. A., "Rock Reinforcement," Bulletin of the Association of Engineering Geologists, Volume IX, No. 3, 1972.

15. Mearns, R., "Solving a Rockfall Problem in California," Bulletin of the Association of Engineering Geologists, Volume XIII, No. 4, 1976.

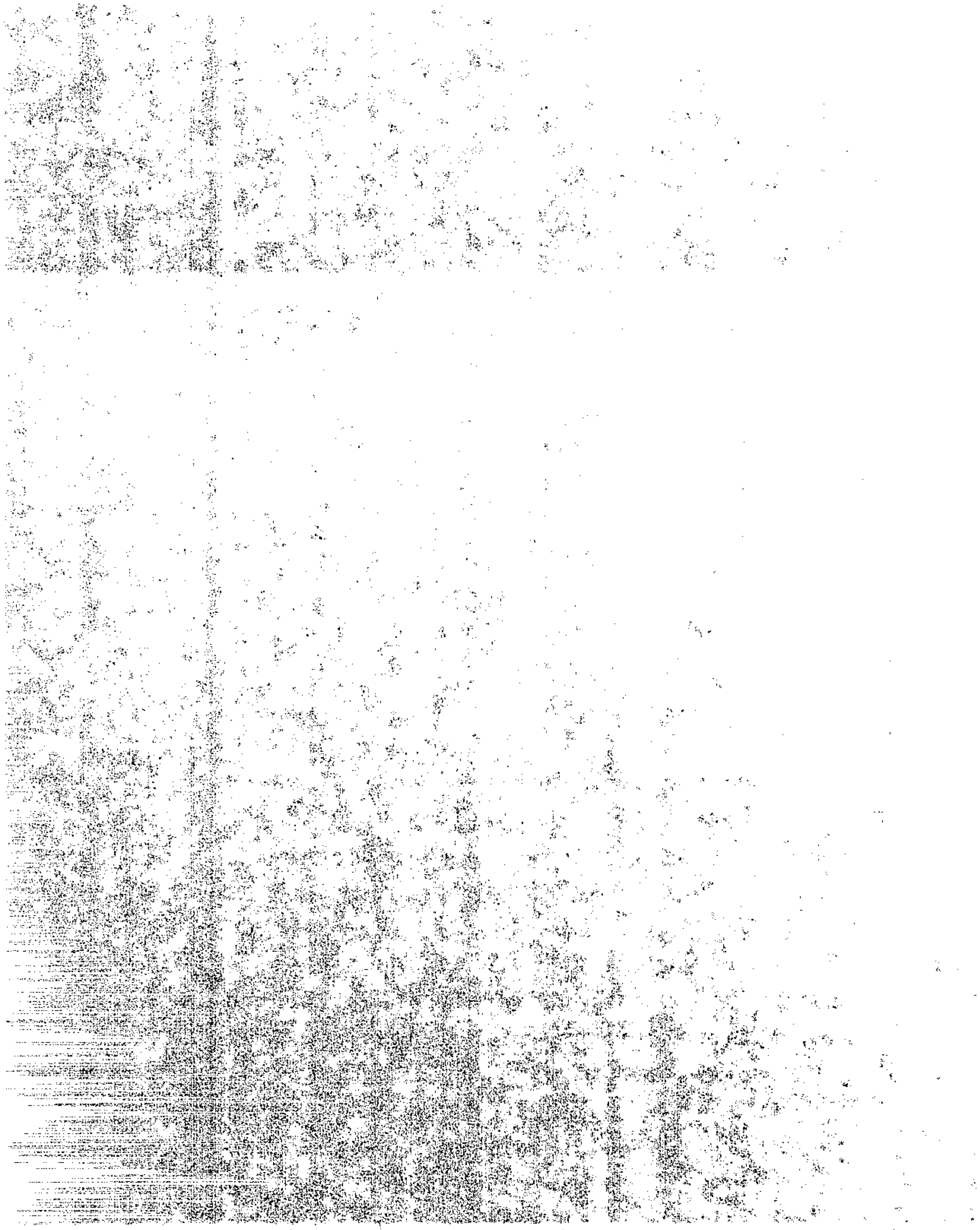
16. Mearns, R. and Hoover, T., "Ravel and Rockfall Protection," Transportation Laboratory, California Department of Transportation, 1973.

17. Muller, L., "The Stability of Rock Bank Slopes and the Effect of Rock Water on Same," International Journal of Rock Mechanics and Mining Science, Volume 1, pp. 475-504, Pergamon Press, Great Britain, 1964.

18. Peckover, F. L. and Kerr, J. W. G., "Treatment and Maintenance of Rock Slopes on Transportation Routes," Canadian Geotechnical Journal, Volume 14, pp. 487-507, 1977.

19. Piteau, D. R. and Peckover, F. L., "Engineering of Rock Slopes," Chapter 9 in Landslides Analysis and Control, Special Report 176, National Academy of Sciences, Washington, D.C., 1978.

20. Ritchie, A. M., "Evaluation of Rockfall and Its Control," Highway Research Record Number 17, Highway Research Board, National Research Council, Washington, D.C., 1963.



APPENDIX A

CHOOSING MITIGATION MEASURES

APPENDIX A

CHOOSING MITIGATION MEASURES

Published articles and the correspondence we received on rockfall agree that each rockfall problem requires a unique solution. The methods listed in this report should be examined for proper application to the situation and then designed for the physical setting.

The best time to solve or prevent rockfall problems is during the design of the roadway. However, many rockfall sites on existing roads also require solutions.

To solve a rockfall problem, physical data about the site are needed, along with information about the relative importance of the road, so that the acceptable level of risk may be assigned.

Mitigation measures are listed in three categories in Figure 6. Peckover and Kerr (1977) state that stabilization methods should be considered first because they generally result in minimum maintenance and provide long-term solutions. Protection methods, considered next, may provide an economic and positive solution. Warning methods do not solve the problem and may result in increased maintenance. However, they may be the only immediately applicable mitigation.

The cost of mitigation measures has been difficult to obtain. When costs are available, generalization for use at other sites is even more difficult. Because of problems in estimating costs, a cost rating number (or range) has been assigned to each mitigation measure. This number is to be used for computing the priority for repair of a rockfall site. A low rating number means a relatively low cost.

This appendix is designed to be used as an aid in choosing mitigation that will be feasible at a particular site. Often the best mitigation will include more than one method. For example, wire mesh fence is often combined with widening at grade.

The flow chart shown in Figure 15 should not be considered the definitive approach to solving rockfall problems, however, it can be used as a guide to develop the mitigation for a specific site.

There are two different ways that rock can reach the traveled way; one is by free-fall and the other is by roll. If the rocks reach the road by roll only, then the only mitigation needed is something that restricts that roll. However, if rocks free-fall onto the traveled way, the problem may be solved by restraining the rocks in place, by protecting the roadway, or by relocating the roadway. The choice of mitigation will depend on site conditions and cost.

Identify Type of
Rockfall Problem

Roll Onto Traveled Way

Consider:
- wire mesh fence*
- metal guardrail
- Jersey barrier
- earth berm
- catchment ditch

Free-Fall Onto Traveled Way

Restrain Rocks

Consider:
- rock bolts
- dowels
- shotcrete
- gunite
- anchored wire mesh
- cable lashing
- concrete buttress
- flatten slope

Protect Roadway

Consider:
- widen at grade
- steel H-beams and timber lagging
- scale or trim
- draped mesh
- rock shed

Relocate

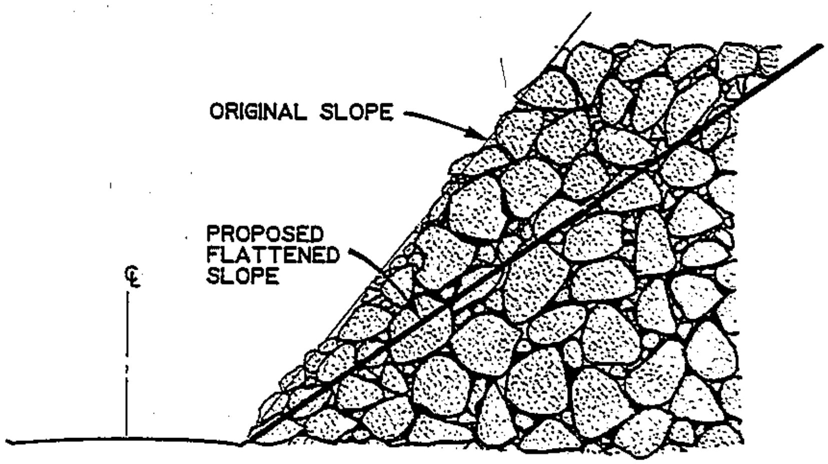
Consider:
- design to geology
- controlled blasting
- subsurface drainage
- retaining walls
- tunnel
- rock shed
- bench

*For rocks up to 1-1/2 feet in diameter.

Figure 15. Flow Chart for Considering Rockfall Mitigation Measures

Flatten Slope

Slopes experiencing rockfall can be flattened to some angle that will eliminate it. A stereonet analysis of discontinuities may show what the proper angle should be. It is necessary to use construction techniques on the redesigned slope that will leave a face with minimal disturbance. Adverse joint orientations may cause the required slope angle to be as flat as the angle of friction on those discontinuities.



FLATTENED SLOPE

Benefits

* Uses standard construction techniques
* Proper slope design will eliminate rockfall

Cautions

* May create a very long exposed cut face
* May require the removal of large volumes of material
* May disturb other areas during reconstruction

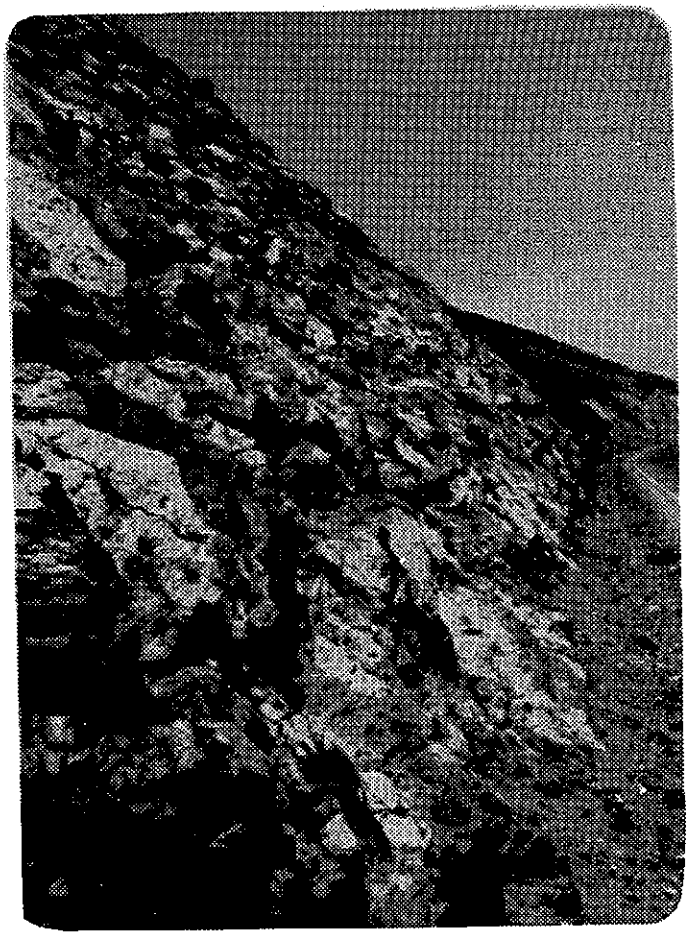
Cost Rating

2 - 4

Scaling or Trimming

Scaling is the removal of rocks and material (that are marginally stable) from the face of the slope. This is done by specially trained crews using pry bars and other tools to dislodge the rock, or it can sometimes be done by using a crane with a bucket to scrape the surface of the cut.

Trimming is the careful drilling and blasting away of overhanging rock.



Benefit

* Can be done quickly

Cautions

* Requires specially trained personnel and equipment
* Scaling usually is not a permanent solution. Trimming of rock may be a permanent repair.

Cost Rating

1

Design to Geology

This mitigation measure includes an almost infinite range of slope designs. Basically, it is a matter of designing the slopes to correspond to the materials rather than cutting the materials to an arbitrary slope angle. The New Mexico Department of Transportation has used it effectively in dipping beds of alternating hard and soft material. Other states have fitted benches at the change in materials to minimize rockfall. A geotechnical study is required to develop the slope design.

No Photo Available

Benefits

* Provides a good solution to the rockfall problem as part of slope design

* Maintenance will be low

Caution

* May incorporate other measures such as benches and widening at grade

Cost Rating

3

Controlled Blasting

Controlled blasting methods use closely spaced holes with light charges evenly distributed in the blast hole. The object of controlled blasting is to leave a cut face that has minimal disturbance. It can make the difference between a stable slope and one that will have excessive rockfall. Any slope that requires blasting should be constructed with controlled blasting techniques. It is generally used with other mitigation methods such as design-to-geology, benches, and widening at grade.

Benefits

* Provides stable slope in rock
* Allows steepest possible slope to be used
* Reduces maintenance costs

Cautions

* Slight increase in initial cost
* Requires knowledgeable blaster and resident engineer
* Used with other mitigation measures

Cost Rating

3

Subsurface Drainage

Subsurface drainage is used to relieve the hydrostatic head that can develop in fractured rock. It is also used to drain springs and wet areas that may be present in materials composed of boulders in a softer matrix. Horizontal drains are drilled into the hillside to intercept and drain the water before it reaches the surface of the cut, thus increasing the stability of the surface layer. It is often used with other methods.

Benefits

* Can be installed quickly
* Disturbance of the slope is minimal

Cautions

* May be difficult to intercept the water
* Requires maintenance of the drainage system

Cost Rating

2

Rock Bolts or Dowels

Rock bolts and dowels are used to fasten a rock in place, or when used in a properly designed pattern, will knit together broken rock and cause it to act as a larger mass. Bolts and dowels are installed by drilling holes into the rock, placing a bolt or dowel in the hole, and fastening all or part of the bolt or dowel in the hole. Bolts are then tensioned, while dowels are not.

No Photo Available

Benefits

* Can be used to stabilize individual blocks or very specific areas
* Steep slopes can be stabilized
* Disturbance of the slope is minimal

Caution

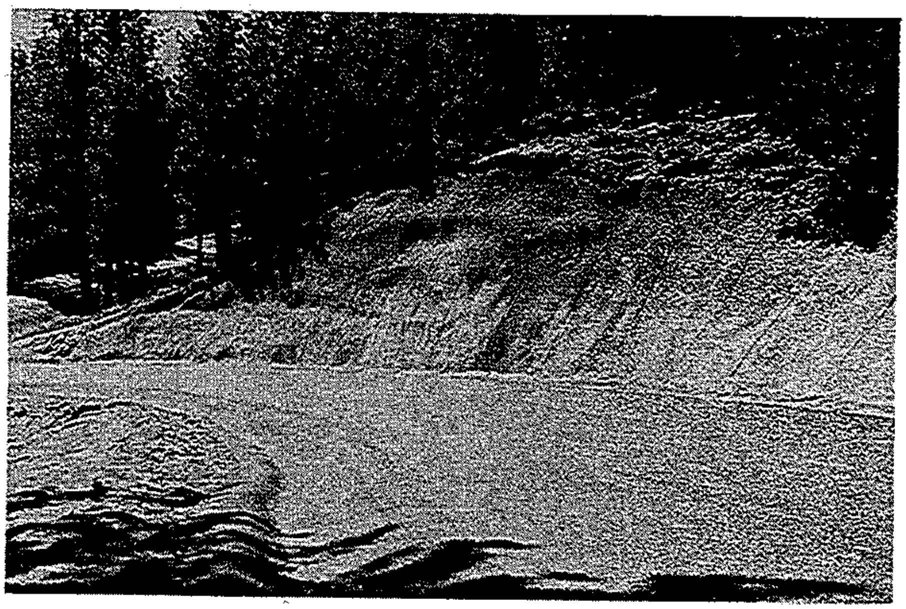
* Some slopes may not be accessible safely

Cost Rating

3 - 4

Shotcrete or Gunite

Shotcrete is pneumatically applied concrete having a maximum size of 3/4 inch aggregate. Gunite is similar but contains smaller aggregate. Wire mesh is used for reinforcement and rock bolts or dowels can be used to anchor the shotcrete to the rock. Weep holes for drainage must be provided. Shotcrete is applied in layers of three to four inches. Each layer is allowed to set before applying the next one.



Benefits

* Used to protect surfaces that are subject to rapid weathering
* Used to construct structural support of overhanging rock
* Can be applied over uneven surfaces if proper methods are used

Caution

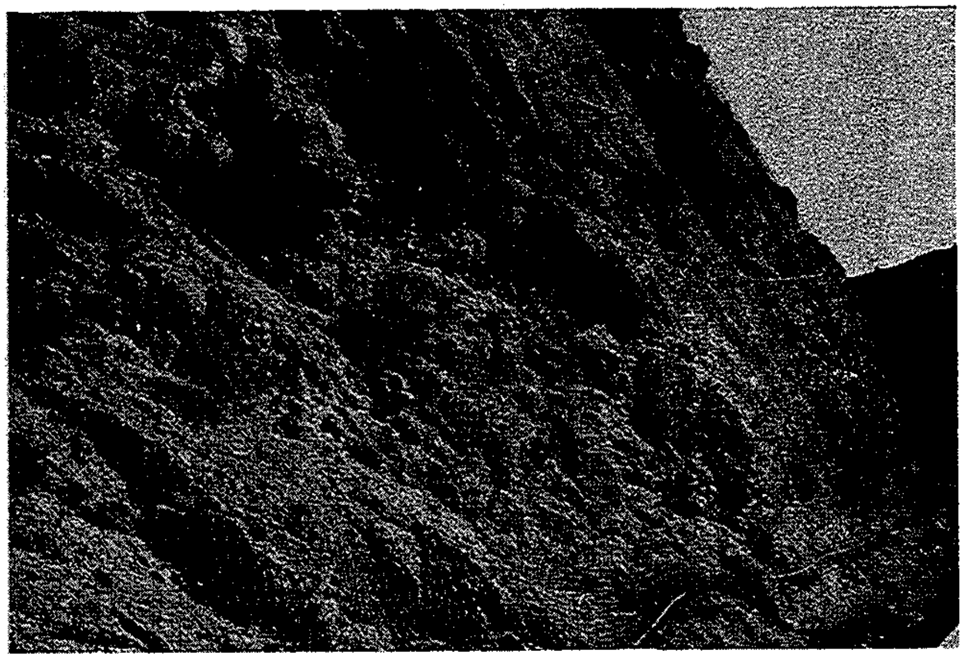
* Drainage is essential

Cost Rating

2 - 4

Anchored Wire Mesh

Anchored wire mesh, as its name suggests, is a wire mesh that is anchored to the slope using rock bolts or dowels. The intent is to pin the mesh close to the rock surface. A reasonably smooth surface is needed for best results. Rocks are kept in place beneath the mesh as opposed to allowing the rock to migrate downslope under a draped mesh.



Benefits

* Used to contain a surface of broken rock
* Keeps rock in place
* Used on steep slopes

Caution

* Access may be difficult

Cost Rating

3

Cable Lashing

A large rock, or in some cases a separate mass of fractured rock, can be stabilized by wrapping cables around the rock and anchoring the cable ends to the hillside.

Benefits

* Used to stabilize a large rock in place
* Can be done immediately
* Minimum disturbance of the hillside

Caution

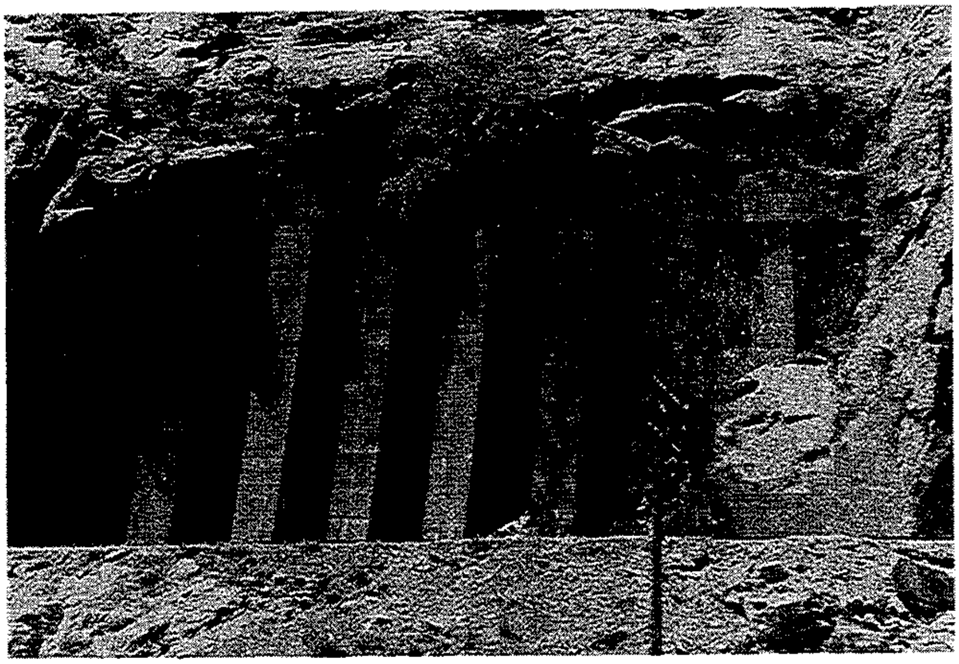
* Limited application

Cost Rating

2

Concrete Buttress

Concrete buttresses are usually constructed as support for overhanging rock when the removal of that rock would be difficult or when removal would worsen the conditions upslope. The buttress could be constructed using layers of shotcrete. Rock bolts may be used if necessary to fasten the buttress to the rock. The method is commonly used in Europe and in Canada.



Benefits

* Used to support massive blocks of rock
* An effective and permanent solution

Caution

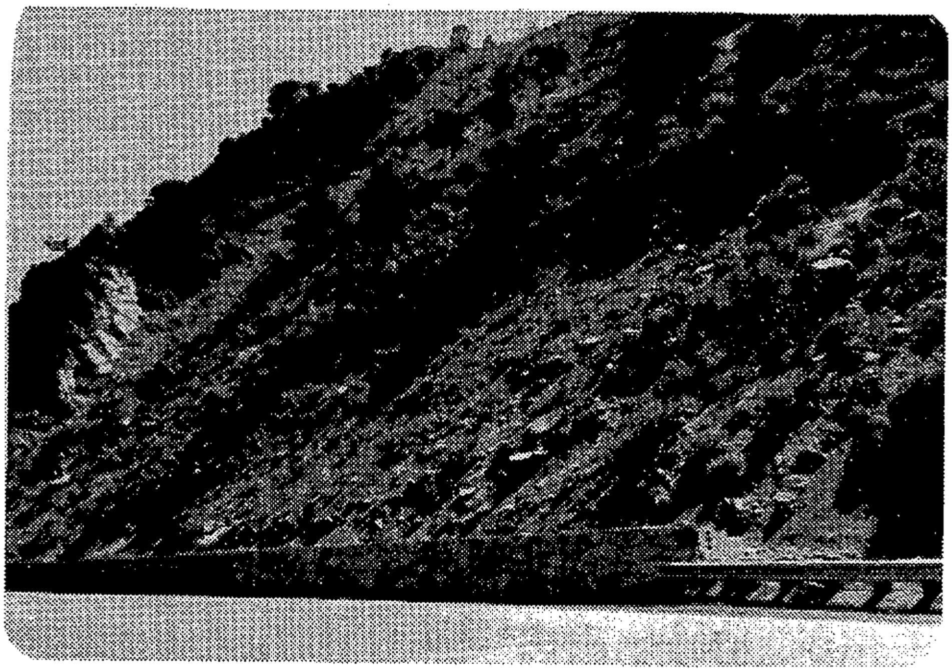
* Limited application

Cost Rating

4

Walls

Walls of various types are used in several different ways to mitigate rockfall. In steep canyons, a wall may be constructed on the downslope side of the road in order to move the road away from the toe of slope. A wall constructed on the upslope side of the road may be backfilled between the wall and slope to create a flatter, more stable slope or to provide a catchment area. In some instances, a wall at road level may be used to prevent rock from reaching the roadway.



Benefits

* Provides a way to move away from the slope
* Provides a catchment area
* Can be used to flatten slope

Caution

* Use Ritchie criteria if wall is to provide catchment

Cost Rating

3

Relocate Roadway

The most positive way of solving a rockfall problem is to avoid it completely by relocating the roadway. Relocation can range from pulling away from the toe of slope so that rocks no longer reach the road to complete realignment of a segment of road to avoid numerous rockfall problems. This may be an expensive solution for many problems, but may be the only workable answer for others. Because rockfall areas are often located in steep canyons, relocation can be a difficult task. Certainly, any relocation to avoid rockfall requires a thorough geotechnical study to be assured that one set of problems is not being traded for another set. Minor relocations may require the construction of a viaduct or mechanically stabilized embankment to provide the necessary width to avoid rockfall. It may also need to be combined with other methods such as a catchment ditch or some type of barrier or fence.

No Photo Available

Benefits

* Use to avoid areas of extensive rockfall
* Very positive solution

Cautions

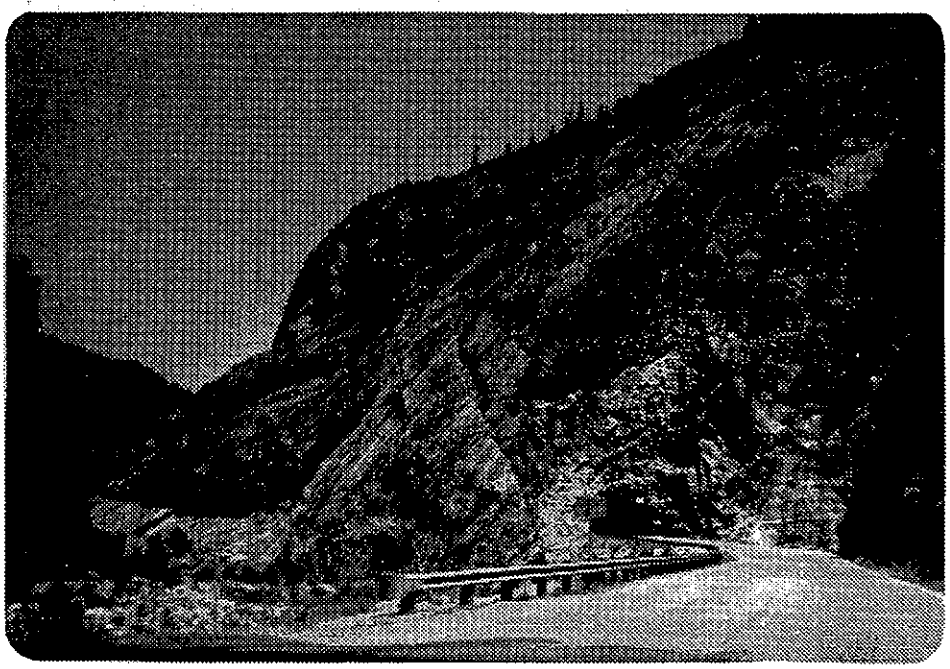
* New alignment must be evaluated
* Requires considerable time to complete

Cost Rating

3 to 5

Tunnel

A properly designed tunnel will avoid all rockfall problems and is, therefore, a positive solution. Rockfall might have to be treated at the tunnel adits. This is a very expensive treatment if used only to solve rockfall problems. However, the incorporation of a tunnel in a new alignment could reduce snow removal, minimize ice on pavements, shorten alignments, as well as provide other design benefits in mountainous regions.



Benefits

* Use in steep mountainous terrain where there are many rocky spurs jutting into a deep canyon
* Avoids all rockfall except at adits

Caution

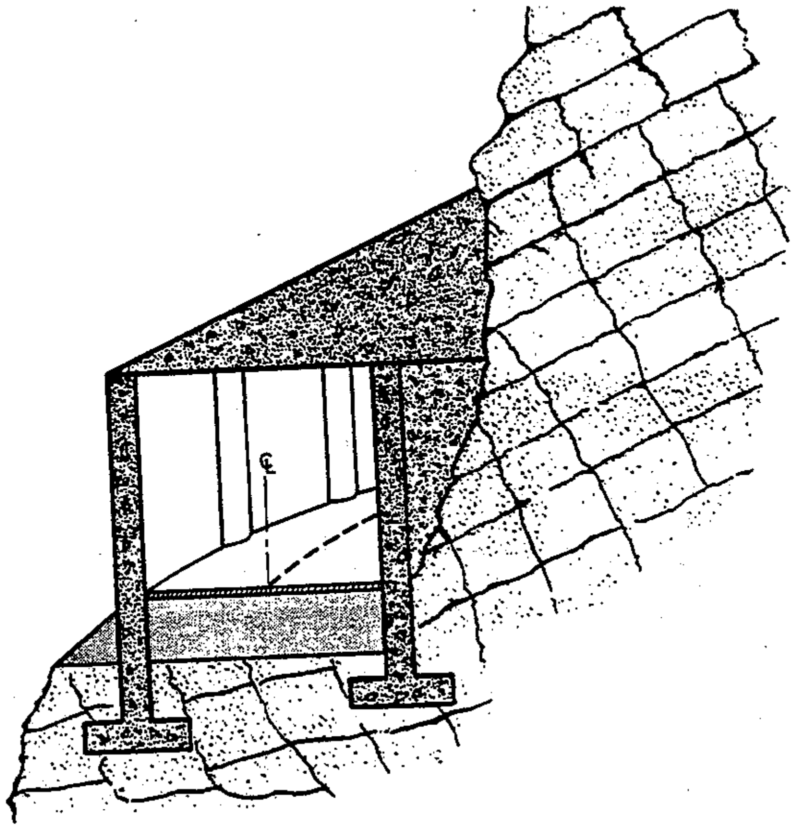
* Long time to construct

Cost Rating

5

Rock Shed

Rock sheds are a positive solution for rockfall problems. They consist of a roof that provides a sloping surface over which the rocks will pass. The roof can be supported in a variety of ways, including being cantilevered in some instances. Design for rock impact is necessary. The shed is usually considered for limited areas of intensive rockfall where there is a steep slope that is conducive to the design of a shed.



ROCK SHED

Benefits

* Use in areas of concentrated rockfall
* Positive repair
* May reduce other types of maintenance such as snow removal

Caution

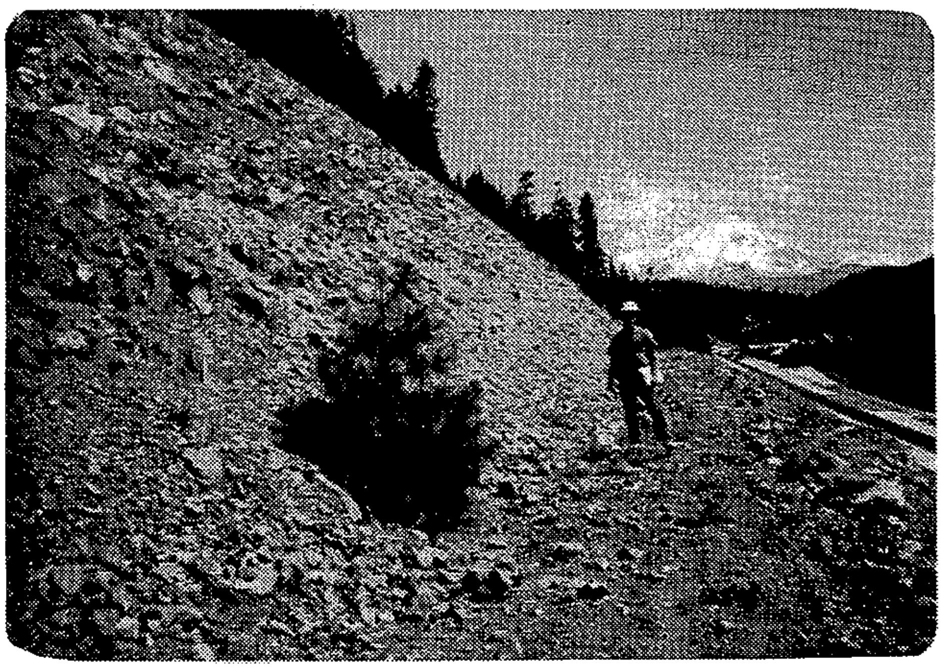
* Requires time to build

Cost Rating

5

Mid-Slope Benches

Mid-slope benches are used to catch rocks or slow the velocity of rocks rolling or bounding down a long cut surface. In California, the standard practice is to place the benches at 60-foot vertical intervals. The width of benches is normally 20 feet. This width is used to provide working room for clean-up equipment on the bench. A bench included in a slope design to catch rock needs access so the bench can be cleaned. If the bench is not cleaned, the debris forms a ramp and launches rocks down the slope. A variable-height bench often provides access and locates the bench at the change between fresh and weathered rock. Mid-slope benches also break up the sheet flow on cuts and reduce erosion that may cause rockfall.



Benefits

* Catch rock rolling down a slope
* Provide drainage
* Usually easy construction
* Constructed relatively quickly

Cautions

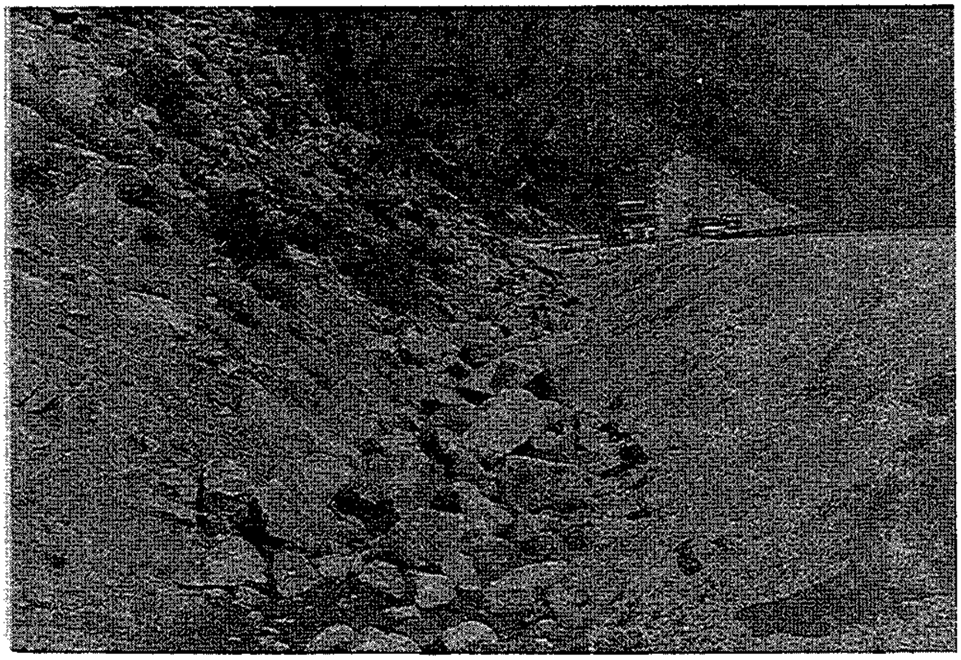
* Rocks may roll over bench
* Benches full of debris act as ramps
* Maintenance is required
* Usually used with other measures to solve the problem

Cost Rating

2 - 3

Catchment Ditch

The catchment ditch was described as a rockfall mitigation measure by Ritchie over 20 years ago (Ritchie, 1963). The criteria provided by Ritchie are used by many states and some foreign countries. The criteria were verified in this study and also in previous work (Mearns, 1977).



Benefits

* Contains almost all rock in the ditch
* Relatively easy to construct if width is available

Cautions

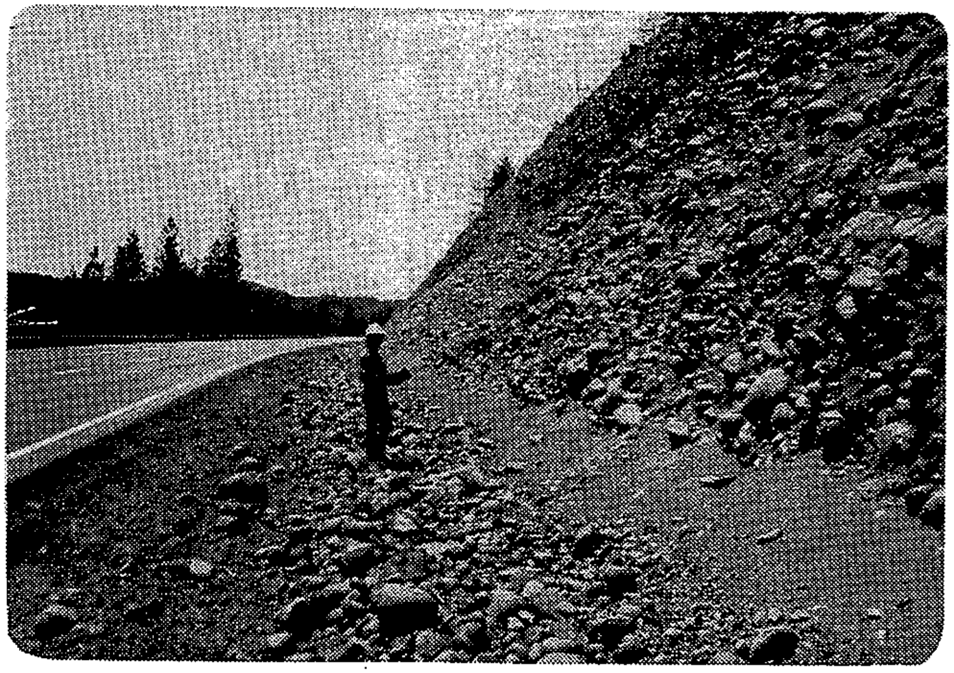
* Dimensions must correspond to Ritchie's tables to be effective
* Some safety hazard may result from the ditch along the road
* May require blasting at toe of slope
* Requires maintenance.

Cost Rating

3

Widen at Grade

Space is provided between the toe of slope and the edge of pavement. By using the widths proposed by Ritchie (1963), this widening can prevent rocks from free-falling onto the traveled way. If the widening is combined with some form of restraint near the shoulder, the roll can also be restricted.



Benefits

* Effective in preventing rocks from free-falling onto the traveled way
* Simple to design
* Uses regular construction methods
* Allows options for restraining rock roll (if needed)
* Provides easy cleanup

Cautions

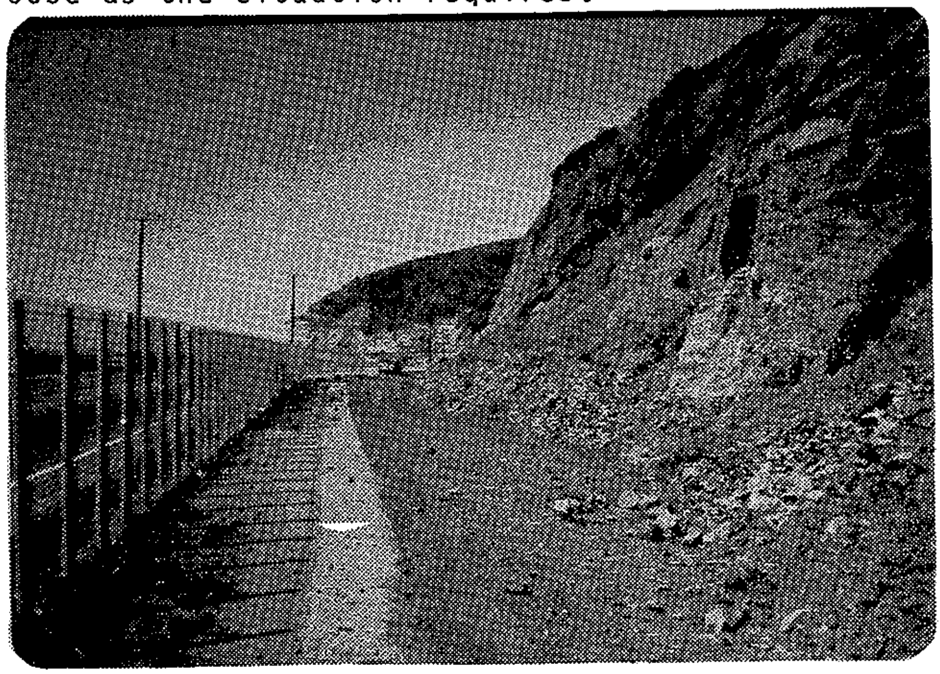
* Dimensions must correspond to Ritchie's tables to be effective
* Additional method needed to contain rock roll
* Room for widening may be difficult to obtain
* Requires maintenance.

Cost Rating

3

Wire Mesh Fence

Chain link fence or gabion wire fence is placed between the shoulder and the toe of the slope. A cable or wire is installed along the top of the fence between the posts. In California, four-foot high right-of-way fence is frequently used because it is readily available. For effective cleaning, the mesh is installed on the highway side so that, as the material builds up on the slope side, the bottom of the fence may be lifted for cleanup. Bottom of the fence may be fastened or left loose as the situation requires.



Benefits

* Effective for catching bouncing rocks up to 1 foot in diameter or rolling rocks to 1-1/2 feet in diameter
* Can be used at the base of a 1-1/2:1 slope to contain ravel and roll
* Readily available

Cautions

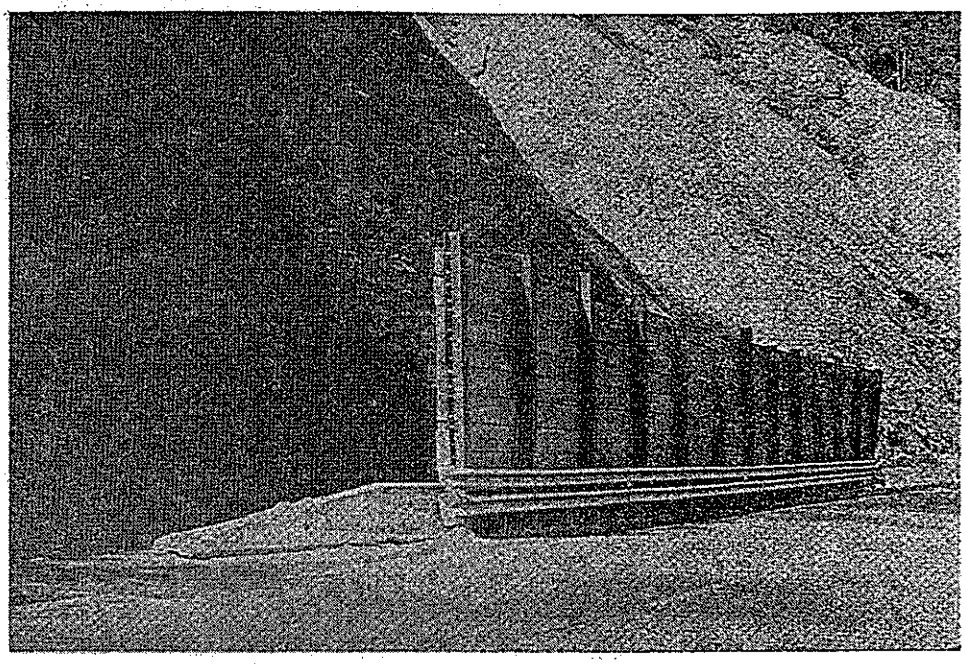
* Rocks will bounce over four-foot high fence if placed at toe of 1:1 slope or steeper. Must be installed proper distance from toe according to Ritchie criteria
* Extensive damage to fence may result when installed in snow country
* Will not stop rock larger than 1-1/2 feet in diameter
* Requires maintenance.

Cost Rating

2

Steel H-Beam and Timber Lagging Wall

This type of wall is used to increase the vertical height to 15 or 20 feet in order to catch flying rock when only minimal widening is possible at grade. The increased height of wall, in effect, increases the width of the catchment area. The wall must be sturdy enough to catch the size of rock on the fly without extensive damage to the lagging. May also be used to increase the temporary storage area for rock.



Benefit

* Provides catchment when widths less than the normal criteria are present at grade

Cautions

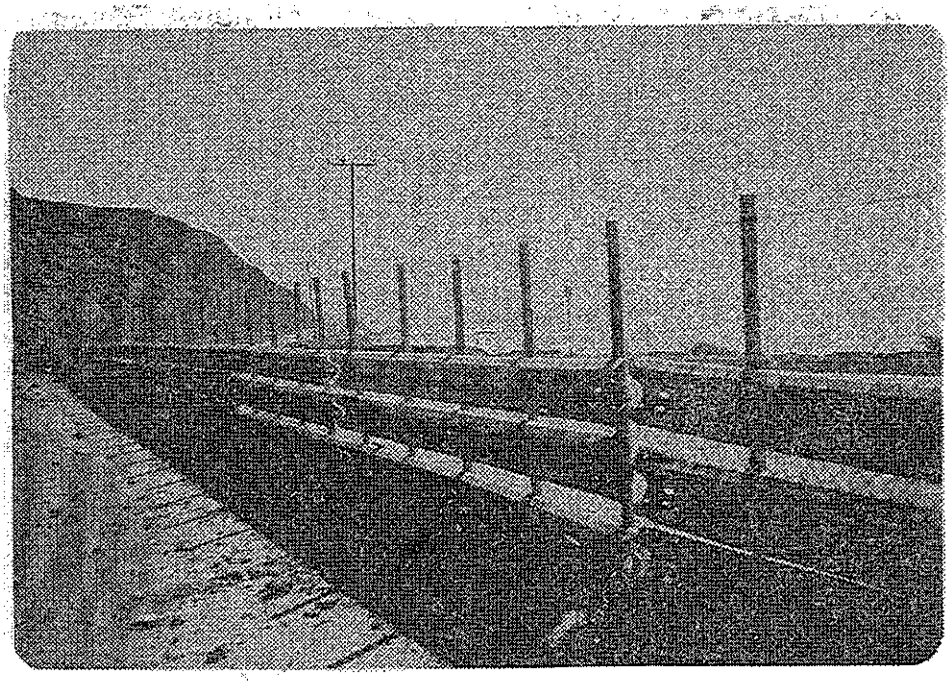
* More costly than fences, berms, movable concrete barriers
* Maintenance required

Cost Rating

3

Metal Guardrail

Metal guardrail is used to restrict rocks of larger size than a wire mesh fence will contain. Usually the rail is bolted on the side facing the cut or on both sides of the posts.



Benefits

* Materials are usually available
* Installation is routine
* Stops larger rocks than a wire mesh fence

Cautions

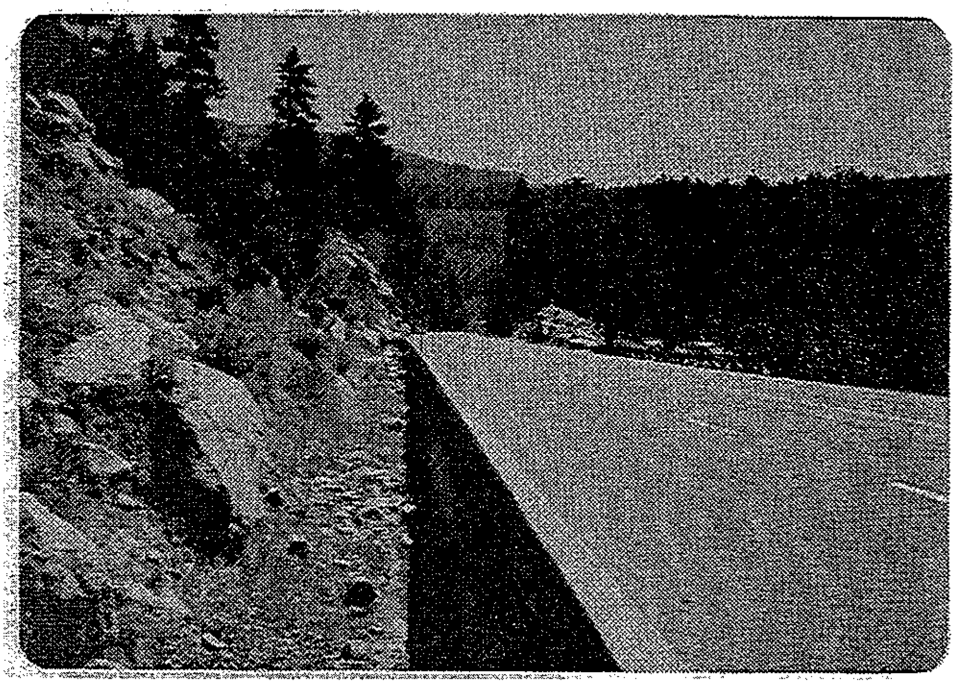
* Small rocks may go under
* Is a restriction along the shoulder
* Maintenance is required

Cost Rating

2

Movable Concrete (Jersey) Barrier

Movable concrete barriers can be used to restrict rocks from rolling on the traveled way.



Benefits

* Contains larger rocks than a wire mesh fence
* Rapid installation
* Removable for maintenance

Cautions

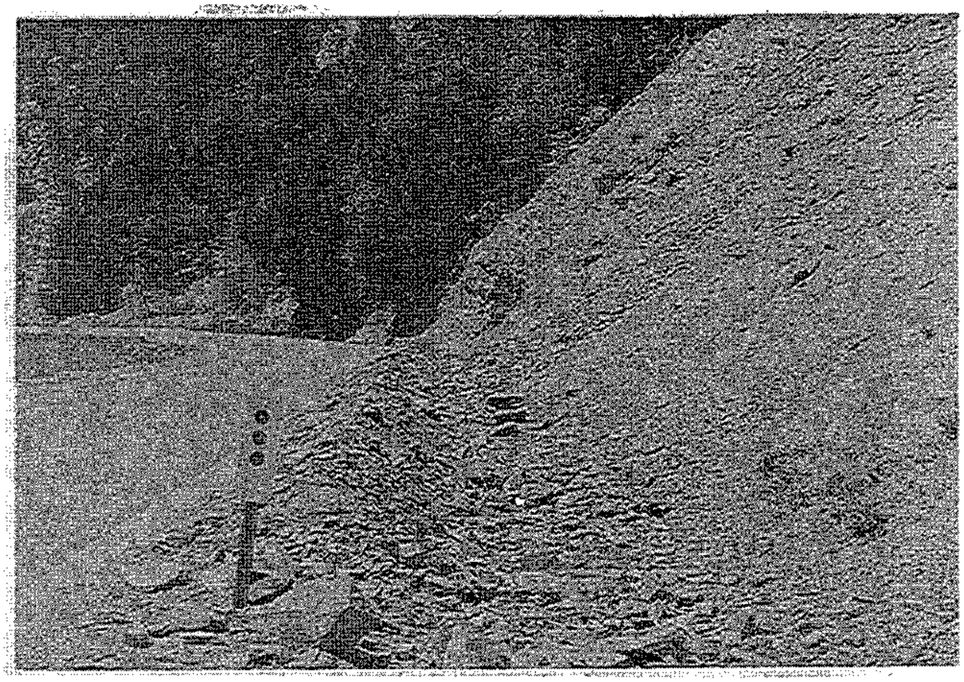
* Low vertical height
* Maintenance required
* Is an obstruction along the shoulder

Cost Rating

2

Earth Berm

An earth berm constructed at a proper distance from the toe of slope provides an effective catchment area for rockfall and restraint of rock roll. In effect, a catchment ditch is created.



Benefits

* Constructed of inexpensive material that is usually available
* Removable for maintenance
* Will contain large rocks

Cautions

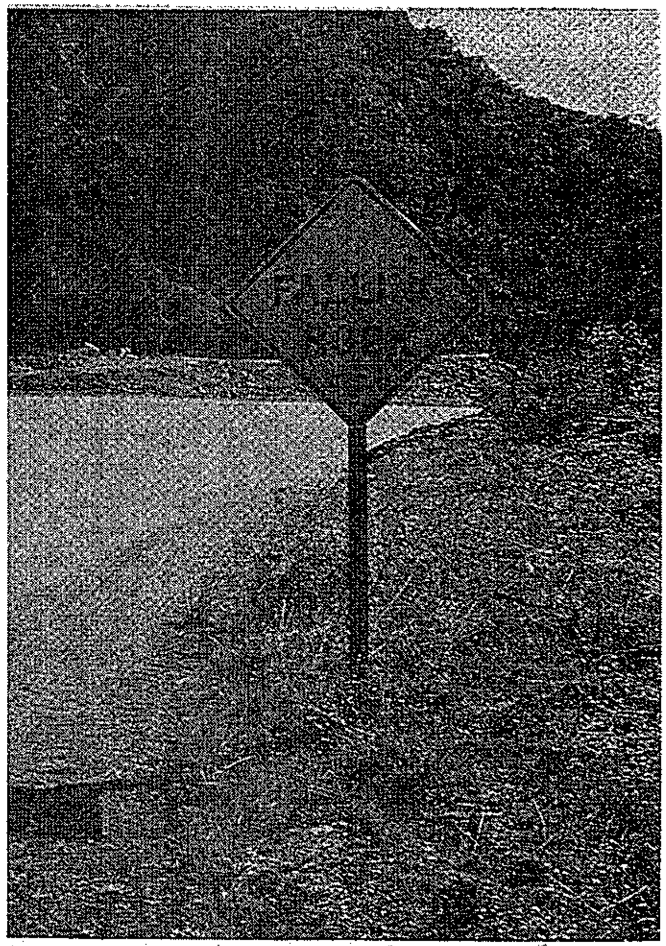
* Must be constructed with the proper dimensions
* Maintenance required
* Needs extra width at grade for the berm

Cost Rating

1 - 2

Signs

Signs have been used along highways for many years to warn of falling rock. Messages such as "Watch for Falling Rock" or "Rockfall Area" are often used. They do not solve the problem, merely alert people to it.



Benefits

* Easy to install
* Can be installed quickly

Cautions

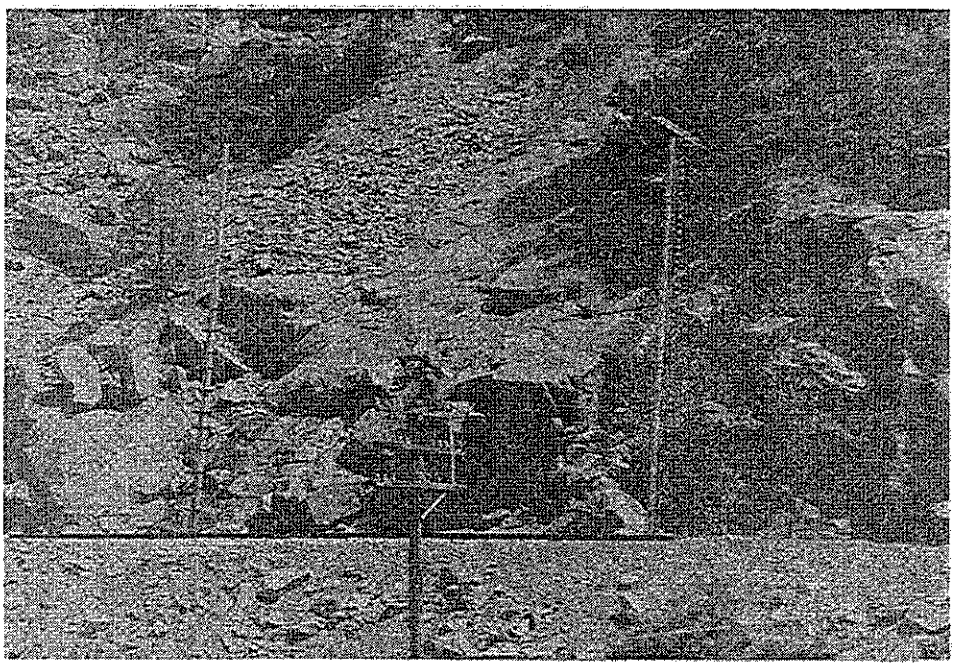
* Does not solve rockfall problem

Cost Rating

1

Electric Fence - Electric Wire

Electric fence or electric wire warning devices have been used for some time by railroads. They are designed to stop traffic in a segment of track if the fence or wire is broken, presumably by a rock. This type of device has had little use on highways because it is more difficult to automatically close a road.



Benefits

* Used to indicate rock has fallen
* Rapidly installed

Cautions

* Does not solve the rockfall problem
* Can be triggered by other things
* Warns after the event
* Needs power supply
* Sounding of alarm requires immediate response

Cost Rating

1

Monitoring

The downslope movement of rock can be monitored in a variety of ways that includes measurement between two points, surveying, automatically recording extensometers, and acoustic emission. These systems work well for monitoring landslides, but most rockfall happens almost instantaneously and there is practically no warning time or reaction time available. These systems might be applicable to a situation where a rock was slowly moving toward the edge of a steeper slope.

No Photo Available

Benefits

* Quick and easy to install
* Can be used until another mitigation is completed

Cautions

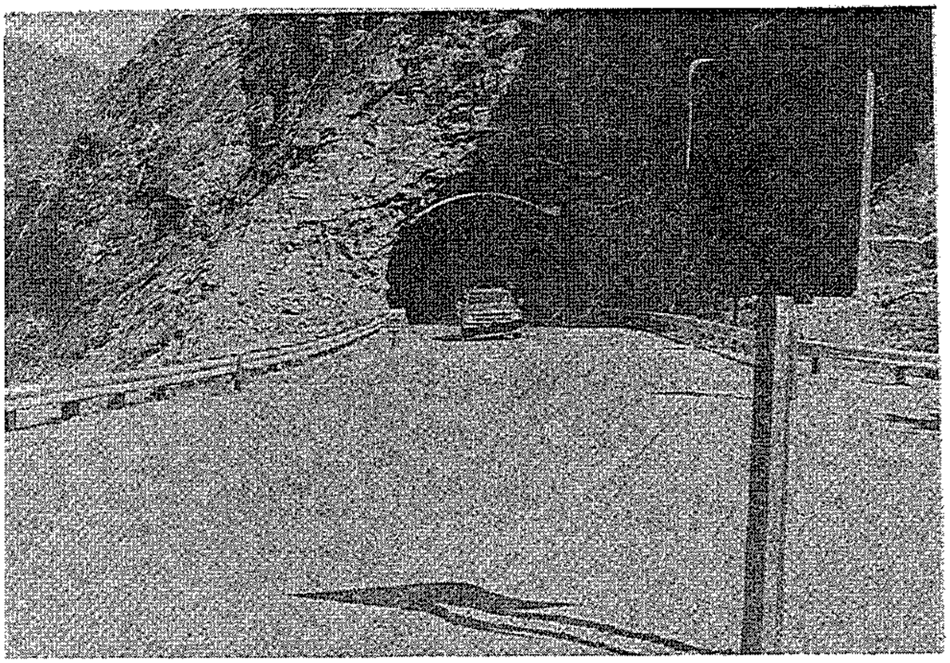
* Does not solve the rockfall problem
* Requires analysis of results
* Warns after the event

Cost Rating

1 - 2

Patrols

Patrolling the roadway provides rapid information about the conditions of the road and occasional rocks can be removed quickly. Patrols are most often used during or immediately after storms. Patrolling does not solve rockfall problems.



Benefits

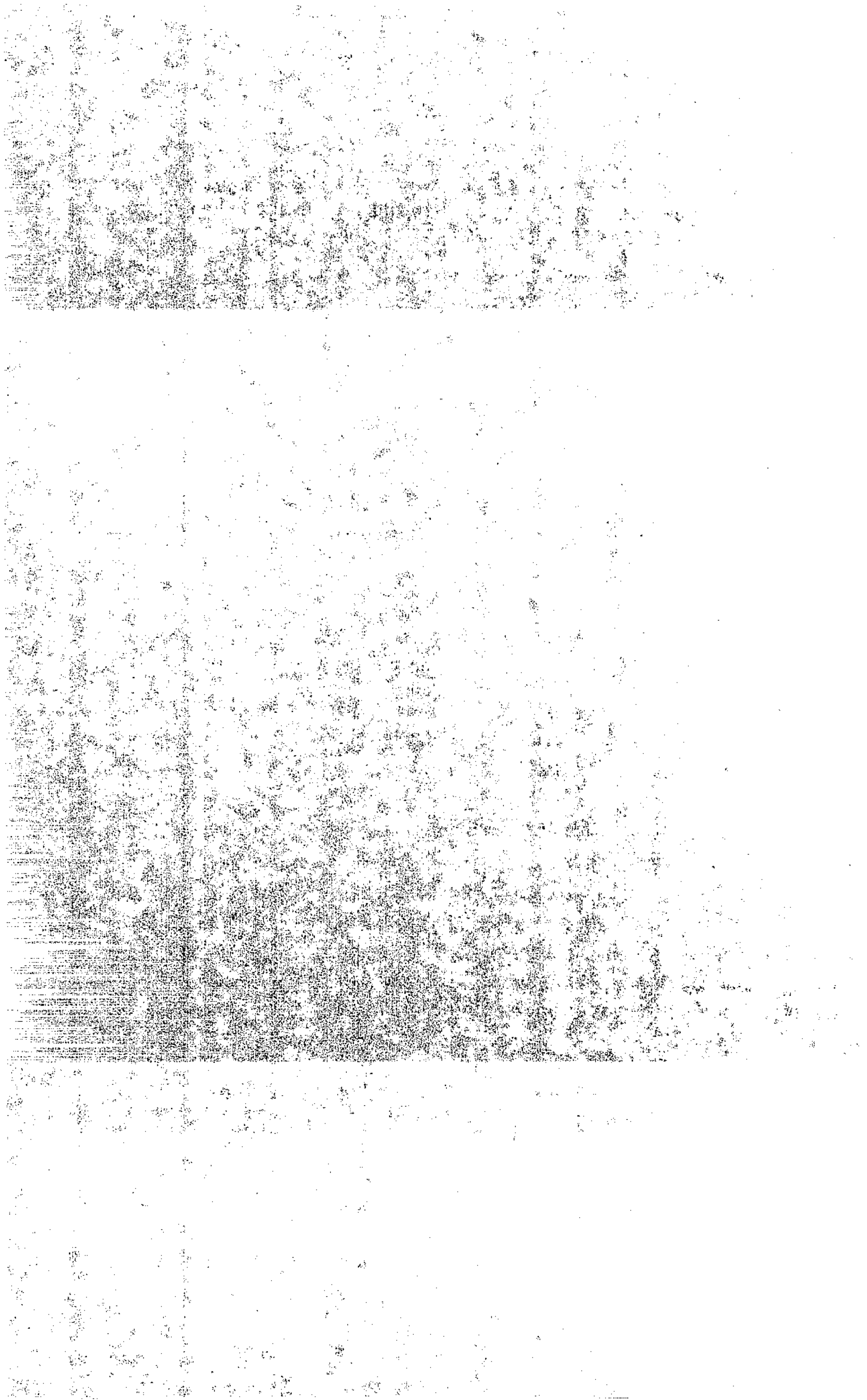
* Used to determine condition of the road and to remove rocks
* Used with existing maintenance personnel

Cautions

* Requires continuous maintenance and the attendant cost
* May be some risk involved
* Does not solve the rockfall problem

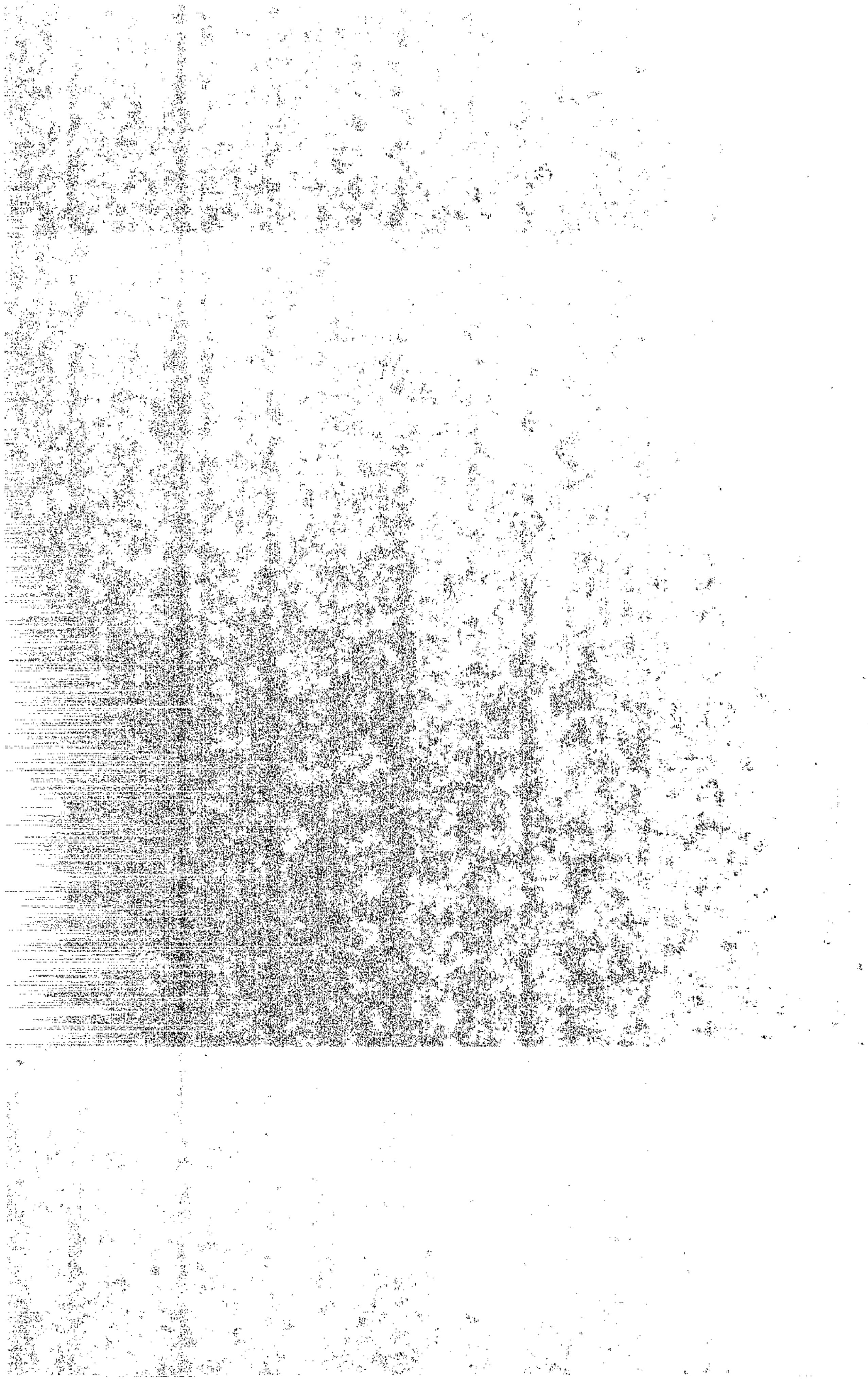
Cost Rating

1 - 2



APPENDIX B

ROCKFALL QUESTIONNAIRE



Date ______________________

Reviewed by ____

____

SITE DESCRIPTION

1. If California: a. District_____b. County_____c. Route ________
   d. Post Mile______e. Other ______________________________
   ____

2. Year of route construction: ______________________________

3. Year that rockfall became a problem at this site: __________

4. Climate
   A. Average annual precipitation ______________________
   B. Temperature range ______________________________
   C. Days of freeze-thaw ____________________________

5. Presence of water during rockfall season
   A. Ground water (describe) __________________________
   B. Surface water
      a. Rain _____ b. Snow melt _____ c. Channeled surface runoff _____ d. Other ________________________
      e. Don't know ______________________________

6. Does wind cause rockfall at this site? Yes_______No________
   A. Is wind the major cause of rockfall? Yes_______No_________
   B. Estimate the wind velocity required to cause rockfall_____
   C. What are the critical months for these winds?___________
   D. What are the critical daily hours for these winds?_______

7. Number of rocks per event ______________________________

8. Time range that rockfall generally occurs:
   A. Month________________to month_______________________.
   B. ________________A.M./P.M. to ________________A.M./P.M.

9. Frequency range of occurrences when rockfall reaches traveled way during critical months.
   A. ___________times per day (e.g. 0 to 3)
   B. ___________times per month (e.g. 10 to 50)
   C. ___________times per season

10. List and/or circle factors that seem to encourage rockfall.

A. Springs B. Seeps C. Rain D. Surface run-off E. Snow melt F. Freeze-thaw G. Wind H. Burrowing animals I. Other (please list): ____________________

J. Person giving information (e.g. maintenance, construction, design, materials) ____________________

11. Mode of travel of rocks (check more than one if applicable).

A. Roll______B. Bounce______C. Free fall______D. Slide______

12. Do rocks land on traveled way? ____________________

A. If so, how far from the toe of slope is impact?__________

13. How far from toe of slope do rocks travel? __________

____

MITIGATION

14. Year the mitigation measure(s) was/were incorporated __________

____

15. Does the mitigation measure(s) appear to be effective, moderately effective, or of little use? ____________________

16. Reasons for using this/these mitigation measure(s). Circle appropriate reasons and/or list others.

A. Performance history B. Low installation cost C. Low Installation time D. Low upkeep cost E. Other ____________________

____

17. Specifications. Give pertinent data for material, spacing of components, etc. that may differ from other installations and that may have a bearing on the effectiveness of the installation. This may be given on a separate sheet. If not known, give any reference that may be available.

18. Was measure(s) installed at time of road construction?

Yes________No________

19. Is mitigation measure affected by snowfall? Yes______No______

A. If yes, describe how ____________________

20. Frequency of maintenance work required at the site.

A. Rock removal ____________________

B. Repairs to mitigating installation ____________________

C. Bench clean-up ____________________

21. Man hours spent for Rock and Sand Patrol in this general area:
   A. During the time shown in 11A ______________________________
   B. During an average year ______________________________

22. Man hours spent per year for inspection and maintenance due to rockfall at the site ______________________________

23. Equipment hours spent per year for maintenance due to rockfall at the site ______________________________

24. Type of equipment used for maintaining the road due to rockfall.
   ____

25. Have rockfall signs been installed for this site or for this general zone? Yes _____ No _____

26. What could be done to decrease rockfall onto the travelled way?
   ____
   ____
   ____

27. Please give any additional comments that you feel are pertinent to the rockfall problem at this site. ______________________________
   ____
   ____
   ____

FIELD INFORMATION

1. Date of review ____________________

2. Reviewed by ____

3. Source of falling rock
   A. Man-made slope ________
   B. Natural slope ________
   C. Don't know ________

4. Approximate diameter of rocks that move down-slope (give range)

   ____

MITIGATION

5. What mitigation measures are used or installed at this site? For example: A. Widening at grade B. Benched C. Wire mesh fencing D. Draped wire mesh E. Catchment ditch F. Berm G. Gabion H. Wall I. Rock shed J. Rock bolting K. Dowels L. Grout M. Shot-crete N. Chemical treatment O. Plastic spray-on product P. Slope scaling.

6. Describe (attach sketch if feasible) ____________________

   ____

   ____

7. What is the location of the installation in relation to the slope (such as walls, etc.)?

8. What is the approximate diameter range of rocks that reach the traveled way? ________________________________

9. Dimensions of the improvement (overall dimensions) __________

   ____

10. Development of potential rock hazard due to (e.g., fractured rock, differential weathering or erosion, adverse planar surface)

    ____

    ____

    ____

11. Geology
    A. Rock type(s) ____
    B. Degree of weathering
       (fresh, slight, moderate, very, completely)

    ____

    ____

C. Structure ____________________

D. Discontinuities (F=fault, J=joint, B=bedding plane, O=foilation). Give attitude, spacing, continuity, asperities, presence of clay on surfaces.

____

____

____

____

12. Observed ground water conditions

A. Seep(s) = S; Spring(s) = Sp

a. Location(s) ____________________

____

b. Perennial? ____________________

____

13. Surface water

A. Surface drainage leading into the problem area? ________

B. Snow melt ____________________

14. Drainage facilities

A. Method(s) used ____________________

____

____

B. Adequacy ____________________

C. Suggestions ____________________

____

____

15. Natural topography at or above road elevation

A. Road elevation ____________________

B. Slope direction(s) ____________________

C. Steepness and variations of natural slope ________

____

D. Describe soil and rock conditions of natural slope, e.g., % of bedrock exposed, roughness of slopes

____

____

____

16. Conditions below the road elevation (for accident severity).

A. Steepness and variations of slope ____________________

B. Describe soil and rock conditions of slope, e.g., % of bedrock exposed, roughness of slope, vegetation.

17. Description of man-made cut slope

A. Overall dimensions of problem area ____________________

B. Cut slope angle ____________________

C. Bench locations and widths (include bench at grade) ____

D. Amount of reverse slope on benches ____________________

18. Vegetation on studied slope

A. On natural slopes - types and amount

B. On cut slope ____________________

a. What part of this was planted? ____________________

19. Road geometry

A. Lane widths ____________________

B. Median width, if present ____________________

C. Width of shoulder next to rockfall area ____________________

D. Bearing of road. If curved, give beginning and end of study area ____________________

E. Is traffic one way? _____ two way? ________.

20. Shape of rocks:

A. Equant____ B. Tabular____ C. Bladed____ D. Prolate________

21. Roundness of rocks:

A. Angular____ B. Subang. or subrd.____ C. Rounded or well rd.____

APPENDIX C

COMPUTERIZED DATA RETRIEVAL SYSTEM

APPENDIX C

COMPUTERIZED DATA RETRIEVAL SYSTEM

Eighty-four data items were selected from all the data on each questionnaire and entered into a computerized data retrieval system. The computer used to store and process this data is an IBM 360/370. Panvalet File Management System was used for data storage. The Statistical Analysis System (SAS) was utilized to retrieve, modify, and process data in batch mode. The attached "Rockfall Data Users' Guide" describes step-by-step how these data were accessed and manipulated through this system. It also works as a key for the attached Data Dump; each data item is listed with its start column location.

ROCKFALL DATA FILE USER'S GUIDE

ROCKFALL DATA DESCRIPTION FOR SAS

OFFICE OF COMPUTER SERVICES

TRANSPORTATION LABORATORY SUPPORT

Revised : 8 November 1984

ROCKFALL DATA FILE USER'S GUIDE

8 November 1984

The following pages contain instructions to access and manipulate the "TM.EGL.ROCKFALL.MITIGATE" data base to produce SAS reports.

LOGON to SCOPE using the charge code "V190L". SIGN ON to the PANVALET member "TMEGLJCL.SAS". This PANVALET procedure has JCL followed by SAS commands. The SAS commands are altered to develop the report as you wish to see your data. The SAS commands establishes variable names, data selection criteria, and identification and titles for the report.

SAS names can be up to 8 characters long. The first character must be a letter or underscore. Later characters may be letters, numbers or underscores. Special characters ($, &, @, #, -, etc.) other than the underscore are not allowed. Blanks may not appear in SAS names.

Each variable to be printed must be identified in the INPUT list. The variable identification includes the starting column, name, and length of the data field. Each identification starts with "@" followed immediately by the start column number of the field, followed with a blank space, followed with the name, followed with a blank space, followed with field width, and immediately ended with a period ".". Alphabetic information must be indicated by preceding the field width number with "$". The county information may be identified as "@3 county $3.". Numerical information with implied decimal point is indicated by typing a decimal width value immediately following the period. The Postmile value is identified as "@9 POSTMILE 5.2". The input description is terminated with the SEMICOLON (;).

When you do not want to include all observations in the data set being created, you can use a subsetting IF statement. For example, the statement "IF DISTRICT = 3 ;" would result in a data set containing only district 3 records. To select more than one condition the statement may read "IF DISTRICT = 3 OR COUNTY = 'SHA' ;". This selection would include all records of district 3 and all the records of Shasta County. Please refer to the SAS manual for the complete information on subsetting of data files.

Run identifications are entered at the end with a series of TITLE cards. Use either TITLE or TITLE1 for the title to be printed on the first line of the page. To define titles for the second through tenth lines of the page, use the keyword TITLE ending in a number. For example, to define a title for line 3, you might use the statement "TITLE3THIS IS THE THIRD LINE".

Type EXEC in the command position in place of EDIT and ENTER. This will allow you to further modify your report writer to print additional reports. The last execute can be instructed to do dual commands by the typing of EXEE or EXEK in place of EXEC. EXEE will execute the report writer and ERASE your modified report writing instructions. EXEK will execute the report writer and RETAIN the modification permanently in the PANVALET file.

Type LOGO in place of PAN1 and ENTER to log-off the SCOPE session.

Modification to data may be done on-line via TSO (Time Share Option) on the terminal. User is cautioned to logoff TSO when a lengthy interruption of the TSO session is anticipated. TSO charging by Teale Data Center includes terminal hookup time in addition to the cost of individual command execution.

The instructions that follow are the bare minimum to modify your data records in the "TM.EGL.ROCKFALL.MITIGATE" data file.

A. Place an "X" by TSO and ENTER to select the Time Share Option on the terminal. The computer will respond with "ENTER USERID". If not, hit "CLEAR" and type "X" just prior to "-TSO" and hit ENTER.

B. Type in the userid "TRPJB/TPLAN ACCT(V190D)" and ENTER. Wait until message to press enter for "SESSION MANAGER".

C. Press ENTER to activate "SESSION MANAGER" and wait for READY.

D. Type "EDIT 'TM.EGL.ROCKFALL.MITIGATE' DATA NONUM" and ENTER. The computer responds with "EDIT". If "EDIT" does not appear and the "SYSTEM AVAILABLE" light is the only green light on at the far right, press ENTER again and wait.

E. TYPE "FSE" and ENTER. Your data should now appear on the screen. Notice the "PF" at the flashing cursor. This is the command location where you will type in most of the commands. At this time examine the screen closely and note the record numbers shown below the "PF". The data column indicator is above the "PF" as a series of (-) and numbers. The screen displays only 74 columns of your 166 columns data record. You must move the window to examine your whole record. This is done by typing "COL nnn" at the command location (type right over the "PF"). "nnn" is any number between 1 through 166. Hit ENTER and the data on the screen will now be the next 74 columns or less starting in "nnn".

F. Modifications to the data are accomplished by typing in the proper information over the erroneous data and ENTER the changes. The "PF" you see at the command position means Page-Forward. Change the "F" to a "B" and the command will become "PB" to Page-Backward. Now you can "change" the data, "page forward" through the file and "page backward" through the file.

The commands "UP nnn" and "DOWN nnn" are available to move the screen image or window up or down the file of information. To move the screen down 7 lines, type in the command "DOWN 7" and ENTER. The 7th line down should now be at the top of the screen display. To move the window down to a particular line in the file, get the difference from the top line on the screen and the desired line and enter the command "DOWN nnn". If the desired line is less than the top line number, get the difference of the lines and type "UP nnn" and ENTER.

G. To DELETE a record (line of data) type a "D" at the far left of the data line number and ENTER.

H. To INSERT "n" records - (n) is the number of records to be inserted.

(1) Type "In" over the record number of the data preceding the inserts.

(2) Hit "ERASE EOF" to clear the remainder of the record number.

(3) Hit "ENTER" and "n" blank lines will be available for entering the new record data.

I. Type "END SAVE" to save the modifications and terminate the update. "END NOSAVE" aborts the update without permanent changes being made to the data file. The commands must be ENTERed to be executed. "READY" will appear on the screen to indicate that the update has been accomplished. Type in "LOGOFF" and ENTER to discontinue the TSO session. Sign on to PANVALET member "TMEGLJCL.DUMP" on SCOPE and execute the JCL to get a new listing of your updated records.

J. EMERGENCY !!! If you get hung up in TSO for any reason and there appears to be no way of recovery, hit the PA1 key in the middle of the top row of special keys. This action should restore you back to READY or EDIT and you can continue from there. To get back your data screen from EDIT type in "FSE" and enter. Call 322-4620 (TDC Scheduling) for assistance if you are in a panic situation.

ROCKFALL DATA FILE USER'S GUIDE

8 November 1984

TABLE OF INPUT VARIABLES

START COLUMN	FIELD NUMBER	LENGTH	DESCRIPTION	DATA
1		2	District	01 to 11
3		3	County (alpha)	aaa
6		3	Route Number	nnn
9		5	Post-Mile	nnn nn
14	1	1	Source of Rock-fall	M,N or B
15	2	1	Size of Rocks (ft)	1 - 9
MITIGATION METHODS				
16	3	1	Rock Fence	Y or N
17	4	1	Catch Ditch	Y or N
18	5	1	Draped Wire Mesh	Y or N
19	6	1	Widening	Y or N
20	7	1	Benched	Y or N
21	8	12	Other Measures (rockwall, k rail, overhanging fence, berm, scaling, catch fence)	
REASONS FOR LOOSE ROCKS				
33	9	1	Fractured rock	Y or N
34	10	1	Freeze/Thaw	Y or N
35	11	1	Rain	Y or N
36	12	1	Wind	Y or N
37	13	1	Channeled Runoff	Y or N
38	14	1	Snow Melt	Y or N
39	15	1	Springs or Seeps	Y or N
40	16	1	Adverse Planar Features	Y or N
41	17	1	Burrowing Animals	Y or N
42	18	12	Other Reasons (tree roots, truck vibrations, differential erosion, soil decomposition, wild animals)	
GEOLOGY				
54	19	2	Rock Type	IE, II, M or S
56	20	1	Bedrock	Y or N
57	21	1	Fresh	Y or N
58	22	1	Slightly Weathered	Y or N
59	23	1	Moderately Weathered	Y or N
60	24	1	Very Weathered	Y or N
61	25	1	Structure	M, S or U
62	26	1	Discontinuities	Y or N
63	27	1	Groundwater	Y or N

SITE CONDITIONS				
64	28	1	Cutoff Drains	Y or N
65	29	1	Bench Drains	Y or N
66	30	4	Road Elevation (ft)	0 - 9999
70	31	1	Natural Slope Evenness	E,M,U,V,-
71	32	2	Natural Slope Angle	0 - 90
73	33	1	Cut Slope Evenness	E,M,U,V,-
74	34	3	Maximum Slope Height (ft)	0 - 999
77	35	2	Slope Angle at Bottom	0 - 90
79	36	2	Slope Angle at Top	0 - 90
81	37	1	Number of Benches Above Grade	0 - 9
82	38	3	Height of First Bench Up Slope (ft)	0 - 999
85	39	2	Width of First Bench Up Slope (ft)	0 - 99
87	40	3	Height of Second Bench Up Slope (ft)	0 - 999
90	41	2	Width of Second Bench Up Slope (ft)	0 - 99
92	42	2	Reverse Slope at Grade	0 - 90
94	43	2	Reverse Slope on First Bench	0 - 90
96	44	2	Reverse Slope on Second Bench	0 - 90
98	45	1	Number of Lanes	0 - 9
99	46	2	Lane Width (ft)	0 - 99
101	47	2	Median Width (ft)	0 - 99
103	48	2	Width of Paved Shoulder (ft)	0 - 99
105	49	1	Two Way Traffic	Y or N.
SHAPE OF ROCKS				
106	50	1	Equant Shaped Rocks	Y or N
107	51	1	Bladed Shaped Rocks	Y or N
108	52	1	Tabular Shaped Rocks	Y or N
109	53	1	Angular Rocks	Y or N
110	54	1	Subangular or Subrounded Rocks	Y or N
111	55	1	Rounded Rocks	Y or N
CLIMATE				
112	56	3	Average Annual Precipitation (in)	0 - 999
115	57	3	Low Temperature (deg F)	-99 to +99
118	58	3	High Temperature (deg F)	0 - 999
121	59	3	Number of Days Below Freezing	0 - 366
ROCK TRAVEL				
124	60	2	Critical Rockfall Beginning Month	01 - 12
126	61	2	Critical Rockfall Ending Month	01 - 12
128	62	2	Total Rockfall Months	01 - 12
130	63	2	Critical Rockfall Beginning Hour	00 - 24
132	64	2	Critical Rockfall Ending Hour	00 - 24
134	65	1	Roll	Y or N
135	66	1	Bounce	Y or N
136	67	1	Freefall	Y or N
137	68	1	Slide	Y or N
138	69	1	Single Rock Event	Y or N
139	70	1	Do rocks land on the travelled way?	Y or N

140	71	2	Rock Impact Distance From The Toe (ft)	0 - 99
142	72	2	Rock Travel Distance From The Toe (ft)	0 - 99
			MAINTENANCE	
144	73	2	Year Mitigation Was Completed	0 - 99
146	74	2	% Effectiveness of Mitigation Measure	0 - 99
148	75	1	Mitigation Measure Affected By Snowfall	Y or N
149	76	1	" " More Effective with Snow	Y or N
150	77	2	Frequency of Rock Removal Per Year	0 - 99
152	78	2	Frequency of Repairs Per Year	0 - 99
154	79	2	Frequency of Bench Cleanup Per 5 Year	0 - 99
156	80	1	Rockfall Signs in Area	Y or N
157	81	3	Manhours Per Year for Inspection and Maintenance	0 - 999
160	82	3	Equipment Hours Per Year for Inspection and Maintenance	0 - 999
163	83	2	Minimum Width at Grade (ft)	0 - 99
165	84	2	Minimum Width from Toe to Fence (ft)	0 - 99

KEY

START COLUMN	DATA
3	aaa = three letter abbreviation
6	nnn = three numbers
9	nnn nn = post miles to one hundredth of mile
14	M = man-made
	N = natural
	B = both
54	IE = igneous extrusive
	II = igneous intrusive
	M = metamorphic
	S = sedimentary
61	M = massive
	S = stratified
	U = unstratified
70 and 73	E = even
	M = moderately even
	U = uneven
	V = very uneven
	- = not applicable
miscellaneous	Y = yes
	N = no

DATA DUMP


```
REC
NUMB.      KEY       ....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8....*....9....*....0
  1                  01HUM03601615M2NNNYYN           YNYYYNNNNTREE ROOTS  S YNYYYUYNNN0650-32U2305555110025000001I0000212
                     0001YYNNYYN06002010004512020300 24YYNNNY20357051NN050005N0240241100
  2                  01MEN02002284M2NYNNNN           YYYNNNNNNN           S YNNYYMYNNN0375-42V070757500000000000240000212
                     0001YYNYYNN0450241100451103050024YYNNNY0618U 51NN010000N0240240600
  3                  01MEN02004160M3YNNYNN           YYYNYNNNNN           M YNNYYMYNNN0700-32M1754545000000000000000000212
                     0014YYNNYYN0400241100701104061024YYNNNN0036U 76NN010100N0160162403
  4                  01MEN02004190M1NNNYYN           YYYNYNNNNN           S YNNYYMYNNN0700-27N180454510752000000000000212
                     0014YYNNYNN0400241100701104061024YYNNNN0036U 76NN010001N0080083000
  5                  01MEN12803880M2NNNNNN           YYYNNNNYNN           IEYNYYNMYNNN0500-43M100766700000000000050000212
                     0002YYNYYNN0400241100401104060012NYNNNY1017U 05NN000000N0080080200
  6                  01TRI03601642M6NNYYNN           YYYYNNNYNN           M YNYYNMNNNN2300-36U150494900000000000050000211
                     0001YYNYYNN0800001100651004070024YYNNNY25457955NN040000Y0320322500
  7                  01TRI29901791M3NNNYNN           NYYYYNNNNN           S NNYYNSNNNN1000-35U100606000000000000050000212
                     0001YYYNNYY0500101000801004070024YYYNNY1030U 05NN020000Y0040040700
  8                  01TRI29901821N2NNNNNROCKWALL    NYYYYNNNNN           S NNYNNUNNNN1000E40-175404000000000000050000212
                     0001YYNNYYN0500101000801004070024YNNYNY18304980NN020000Y1600400500
  9                  02LAS03601400M2NNNYNN           NYYYNYNNNN           S NNNYYUNNNN4800-25U072515100000000000050000312
                     0001YYNNNNY0300000951500904081216YYNNNN00508075YY010000N0800642100
 10                  02PLU07001220N2NNNNNCATCH FENCE NYYYYNNNNTREE ROOTS  S YNNYNUNNNN2200V41-280585800000000000050000212
                     0000YYNYYNN0700061001801202030024YYNNNY16355576NN250100Y0180061000
 11                  02PLU07005660M2YNNYNN           NYYYNNNNNN           S NYYYYSNNNN3500-09U100454500000000000050000218
                     0007YYYNNYY0300061001801004070024YYNNNN00206575YN020000N0200200700
 12                  02PLU07006200M2YNNNYN           NYYNNYNNNN           S NNNYYSNYNN3500-25U210505110601500000050000412
                     0203YYNNNYY0300061001801004070024YYNNNN00506551YN020101Y0500250905
 13                  02PLU08902710M4NNNYNN           NYYNNNNNNN           S NNNYNUNNNN4600-16V050354500000000000050000212
                     0001YYYNYYN0400001001200304021807YYNNNN0015U 50NN030000N0120120900
 14                  02SHA04406500B2YYNNYN           NYYNNNNNNN           S NNYYNUNNNN3200M35U102424510471400000180000212
                     0001YYYNYNN0400091021000204030024YYNNNN0020U 85NN020105Y0400400800
 15                  02SHA29906650M1YNNYNN           NYYNNYNNNN           S NNYYYSNNNN4000-20M070424200000000000130000212
                     0001YYNNNNY0500040981001003051014YYNNNN0032U 51YY010100Y0640640900
 16                  02SHA29907060M2YNNNNN           NYYNNNNNNN           S NNYYYUNNNN3800-18M070454500000000000080000212
                     0010YYNNNYY0500040981001003050911YYNNNN00157990YY010100Y0640641202
 17                  02SHA29908860B2NNYNNOVERHANGFENCYYYNYNNYNN           IEYYYYNMNNNN3100V35V072767600000000000050000212
                     0000YYNNYNN0400040981201003051012NYYNYY15154690NN010100Y9159150200
 18                  02SIS00500040M2NNNNYN           YYYNNNNNNN           IIYNNYYMYNNY2300-20M265454520601514013050000412
                     1008YYYNYNN0500100981251005080024NYNNNN00226085YY050001Y0240241100
 19                  02SIS00502115M2NNNYNBERM        NYYYNNNNNN           S NNYYNUNNNN3300-15U110424200000000000050000413
                     1009YYYYYNN0500001051201005080024YYNNNN00506090NN010100Y0400402100
 20                  02SIS00502150M2NNNYNN           NYYYNNNNNN           S NNNYYUNNNN3300-07V120454500000000000070000413
                     1009YYNNYYN0500001051201004070024YYNNNN00406099NN010100Y0400403400
 21                  02SIS00502200M2NNNYNBERM        NYYYNNNNNN           S NNYYYSNNNN3300-10V060525200000000000060000412
                     1009YYNNNYN0500001051201004070024YYNNNN00227099NN010100Y0400404100
 22                  03BUT03202910M3YNNNNN           NYYYYYNNNN           S NNNYYUNNNN3100-12M080414100000000000050000213
                     0002YYNNYYN0500151000901204051112YYNYYN0018U 76YN010100Y0600600503
 23                  03BUT03203120M3YNNYNN           NYYYYYNNNN           S NNNYYUNNNN3150-16E150454500000000000090000213
                     0005YYNNNYN0500151000901204051112YYNYYY10407080YN010100Y0600600902
 24                  03BUT03203330M2YNNYNN           NYYYYYNNNN           S NNNYYUNNNN3400-17M060424500000000000110000213
                     0007YYYNNYNN0500151000901204051112YYNYYN0035U 76YN010100Y0600601002
 25                  03BUT16202762M3YNYNYN           YYYYNNNYNTRUCKVIBRATIM YNNYNMYNNN1000-28U180525220601512015130000212
                     0006YYYNYNN0180251090101103051024YNNNNN0006U 99NN010100Y0400240601
 26                  03ED 05002200M2YNNNNN           NNYNNNNNNN           S NNNYYSNNNN2600-11E100454500000000000050000212
                     0201YYYNNYY0400181001001104060024YYNNYY0312U 85NN000000Y0040040200
 27                  03ED 05005910B6NNNNNK RAIL      NYYNYYNNNN           S NNYYNUNNNN6000U31V060374500000000000050000412
```

DATA DUMP


```
REC
NUMB.     KEY       ....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8....*....9....*....0

                    0001YYNNNYN060-100951801104060814YYNYYY05268090NN040100Y0160160300
 28                 03ED 05005920B6YNNNNN          NYYNYYNNNN           S NNYYNUNNNN600U31V06037450000000000000050000412
                    0001YYNNNYN060-100951801104060814YYNYYY05265590NN040100Y0160160300
 29                 03NEV02003795M2YYNYNN          NYYNNNNNNN           S NNNYNUNNNN5300-12M0504242000000000000350000212
                    0001YYNNNYY060-100951201103051012YYNNYN0013U 80YN020100Y0320320700
 30                 03NEV02003985M3NNNYNN          NYYNNNNNNN           S NNYYYUNNNN5300-23U0853560000000000000100000212
                    0001YYNNNYY069-100951201103051012YYNNYN0025U 50YY020000Y0320321300
 31                 03NEV02004060M4YNNYNN          NYYNNNNNNN           S NNYYYSNNNN4900-25U0754343000000000000180000212
                    0001YYNNNYY069-100951201103051012YYNNYN0020U 51YY020100Y0320320802
 32                 03NEV08002485M3NNNYNN          NYYYNNNNYN           S NNYYNUNNNN5650-22U1304541108010000000200000412
                    1010YYNNNYN022-250951800906060024YYNNNN00256040YY030005Y1601302000
 33                 03NEV08002517M3NNNYNN          NYYYNNNNNN           S NNYYNUNNNN5600-25U0954040000000000000170000412
                    1010YYYNNYN022-250951800906060024YYNNNN00386040YY030001Y0600602200
 34                 03NEV08002575M2NNNYNN          YYYYNNNNYN           S NNYYNUYNNN5450-23V2505345204020150201010410412
                    1010YYNNNYYN022-250951800906060024YYNNNN00386040YY030000Y1201001800
 35                 03NEV08002873M4YNNNYN          NYYYNNNNYN           S NNYYNUNNYN5300-28M1904550108015000000050000412
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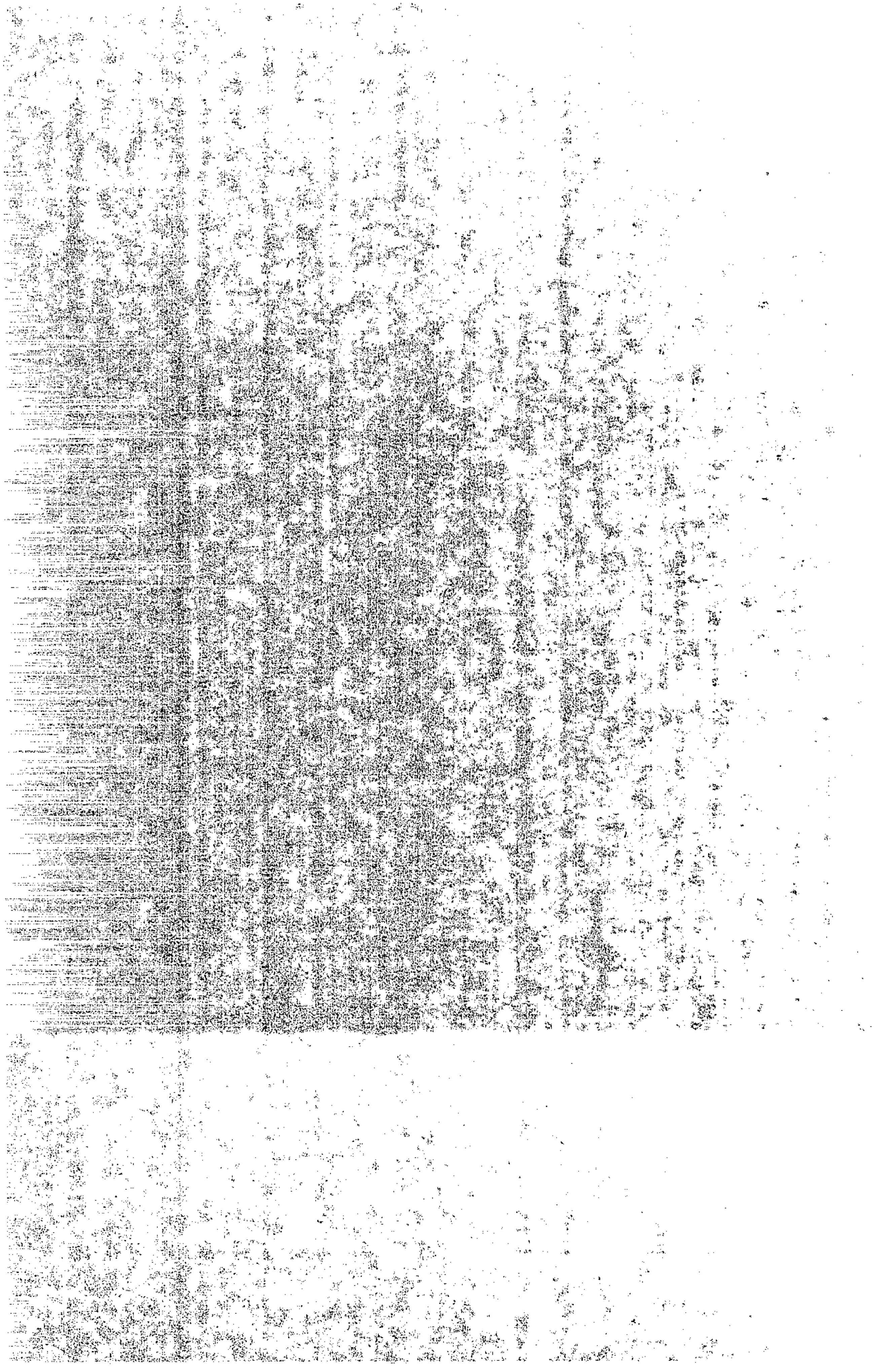

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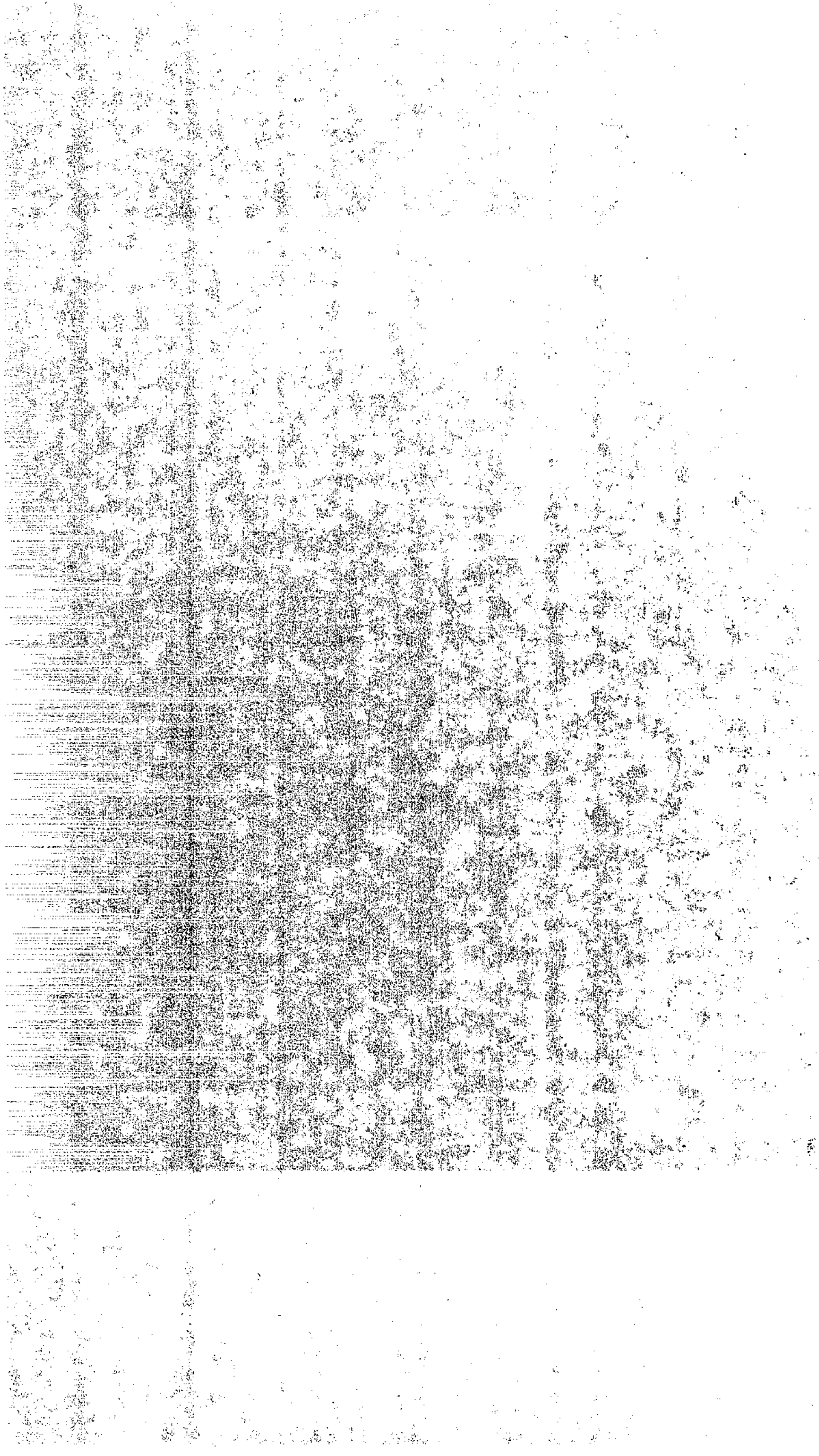
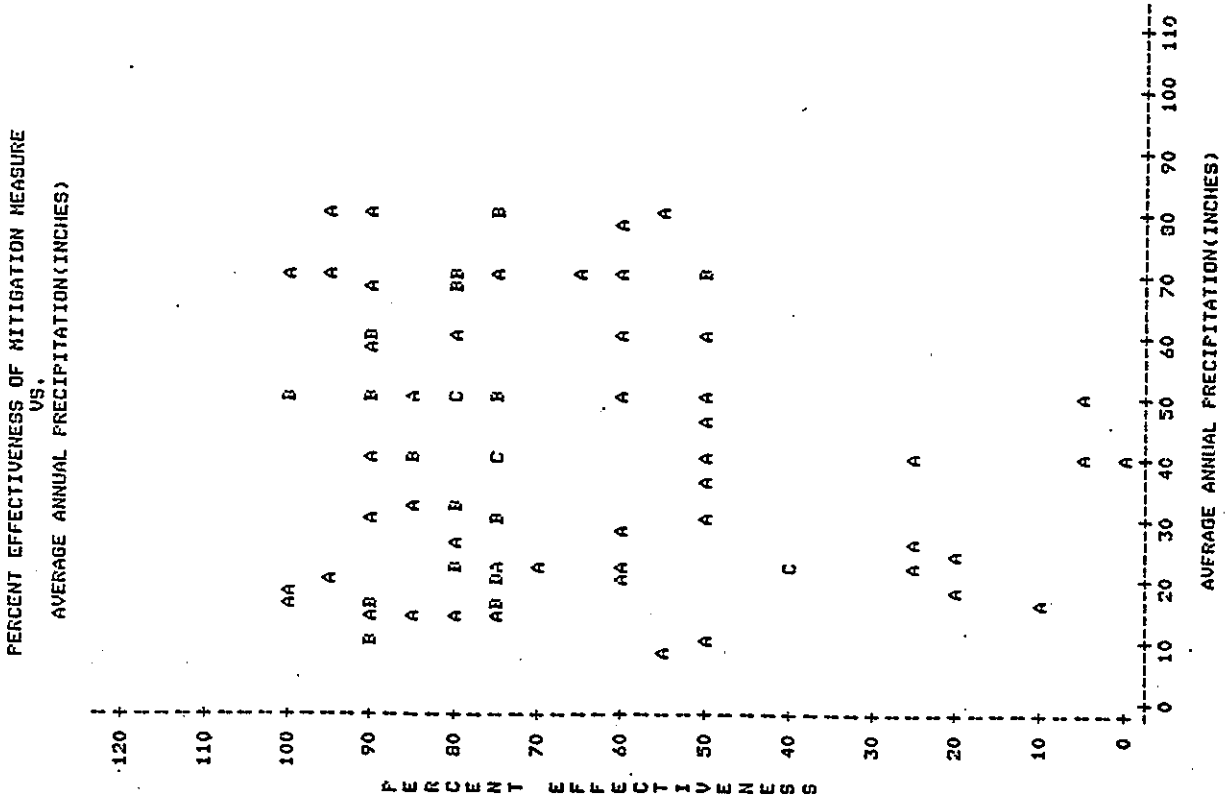
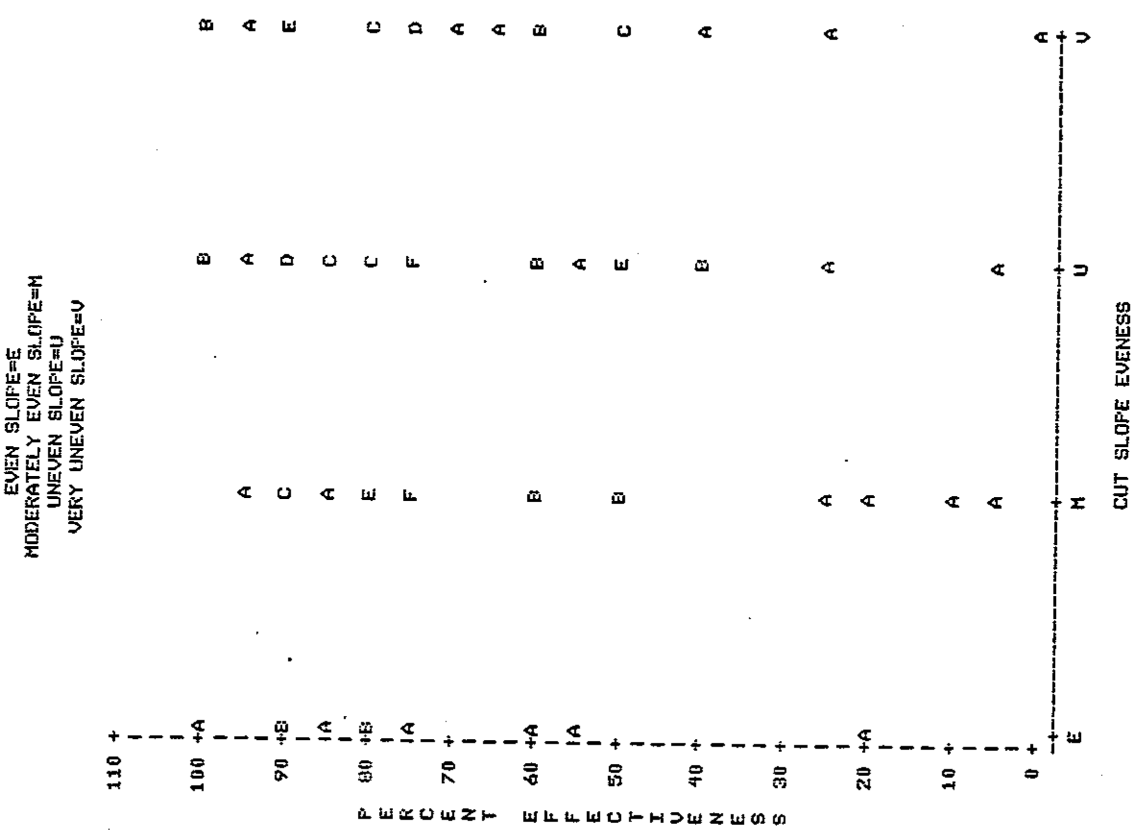
APPENDIX D

Computer Plots that Investigate Percent Effectiveness of Mitigation Measure or Man Hours Spent per Year for Investigation and Maintenance Versus Other Factors.

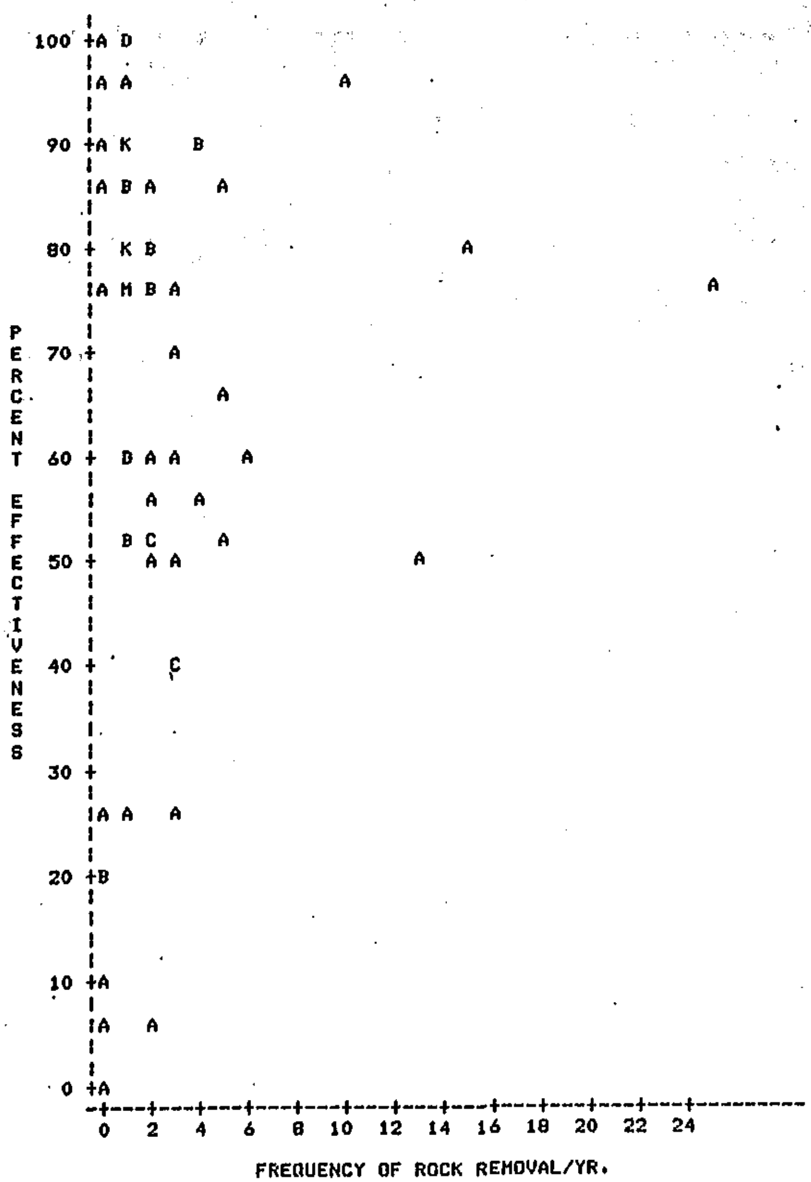
Letter designates number of occurrences for a given point unless otherwise identified.



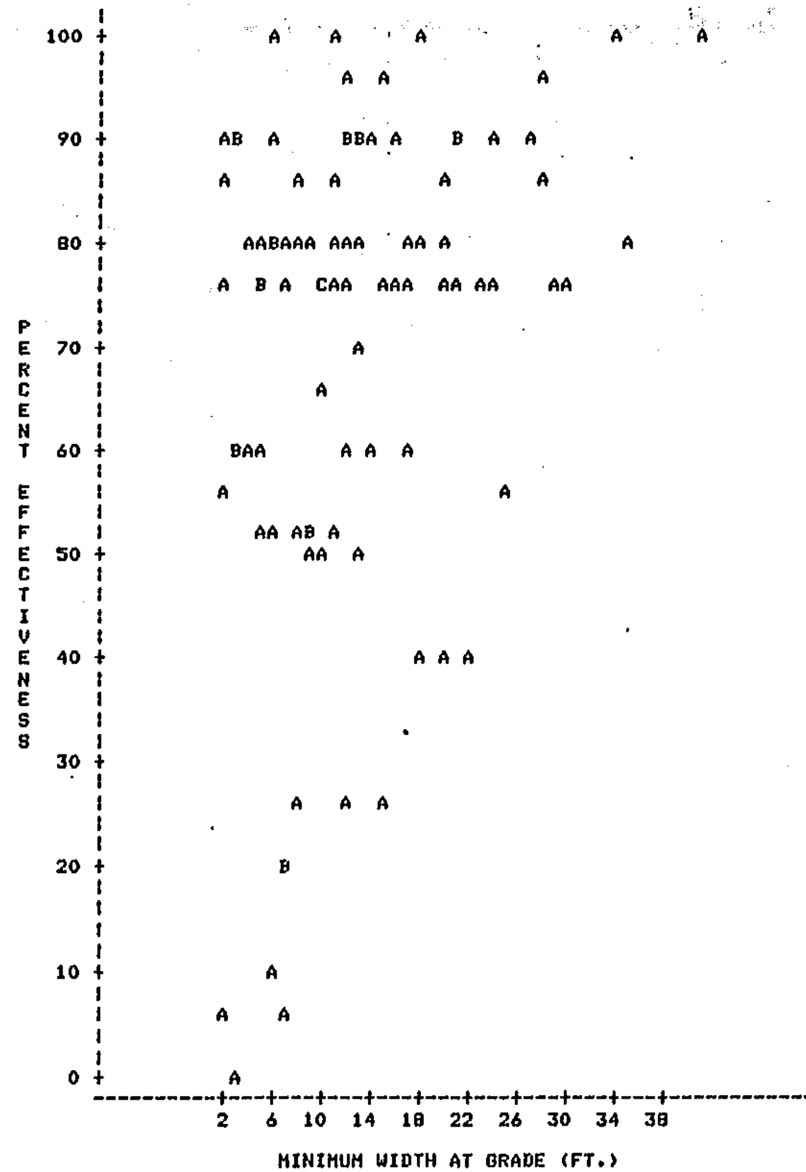

PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
AVERAGE ANNUAL PRECIPITATION(INCHES)
PERCENT EFFECTIVENESS
AVERAGE ANNUAL PRECIPITATION(INCHES)


PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
CUT SLOPE EVENESS
EVEN SLOPE=E
MODERATELY EVEN SLOPE=M
UNEVEN SLOPE=U
VERY UNEVEN SLOPE=V
PERCENT EFFECTIVENESS
CUT SLOPE EVENESS

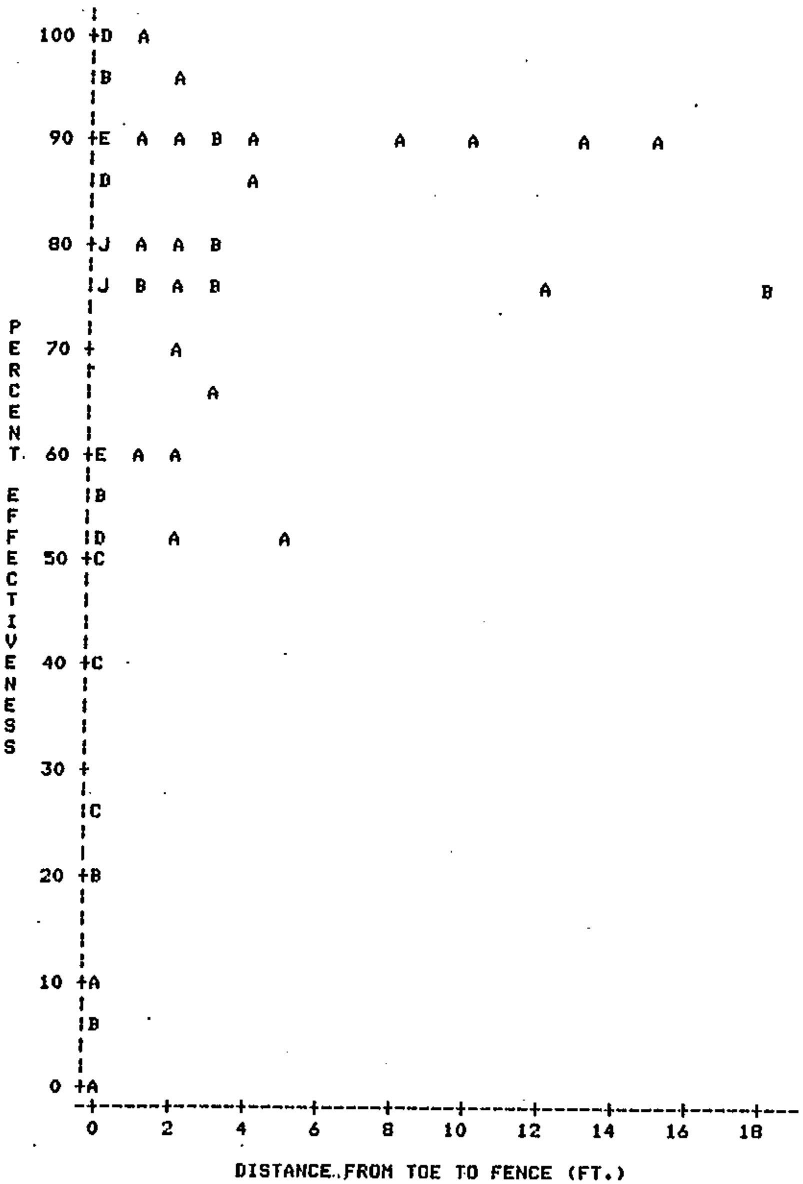
PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
FREQUENCY OF MITIGATION REPAIRS AND ROCK REMOVAL PER YEAR



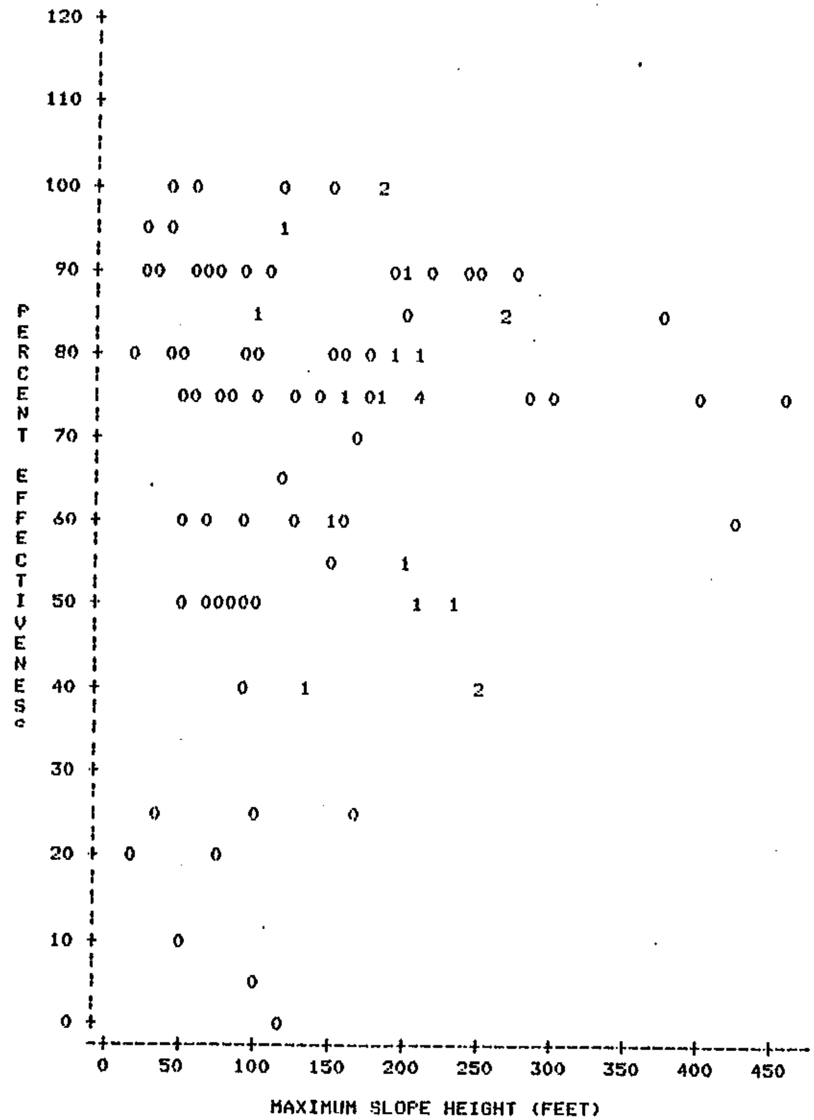
PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
MINIMUM WIDTH AT GRADE



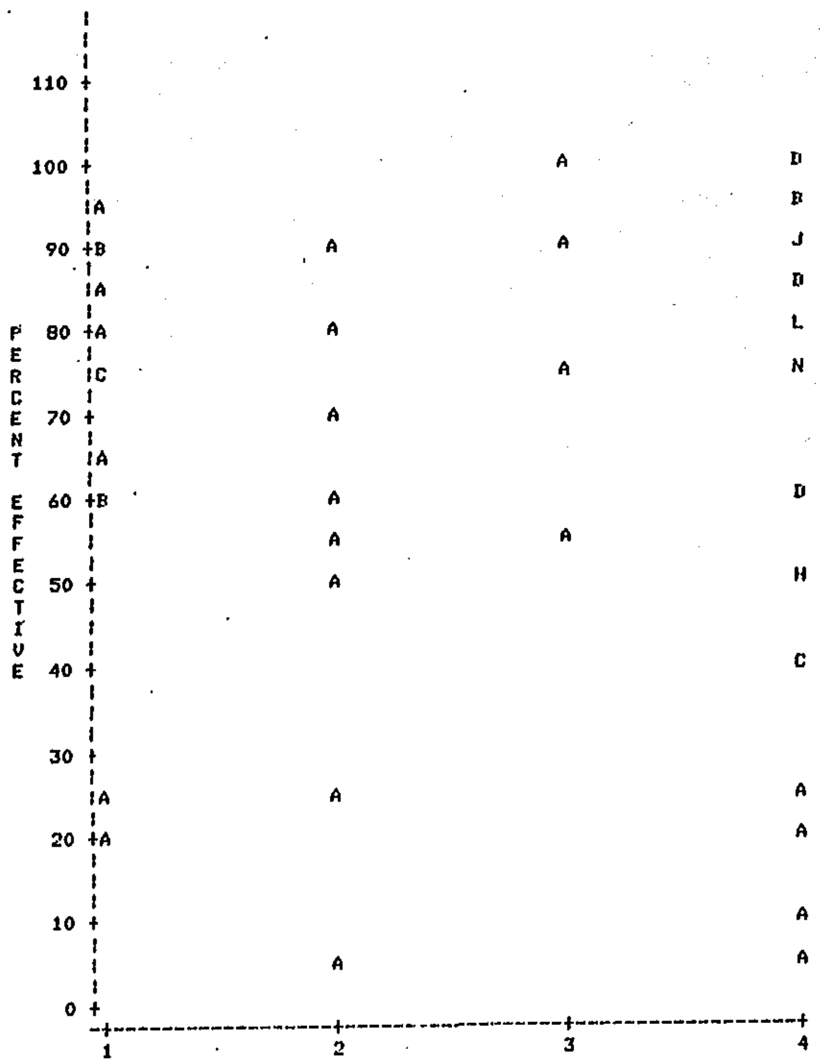
FENCE EFFECTIVENESS VS. DISTANCE FROM TOE TO FENCE



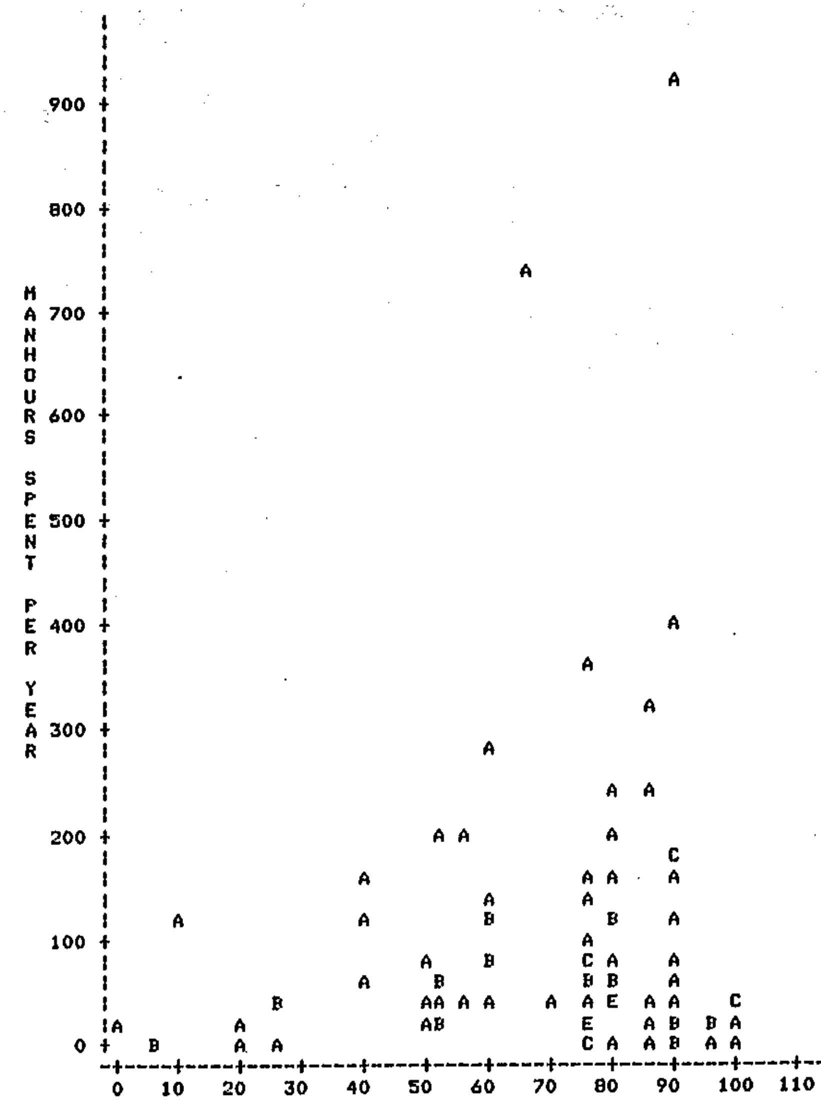
PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
MAXIMUM SLOPE HEIGHT(FEET)
PLOT SYMBOL=NUMBER OF BENCHES ABOVE GRADE



PERCENT EFFECTIVENESS OF MITIGATION MEASURE
VS.
ROCK TYPES
IGNEOUS INTRUSIVE ROCK=1
IGNEOUS EXTRUSIVE ROCK=2
METAMORPHIC ROCK=3
SEDIMENTARY ROCK=4



MANHOURS SPENT PER YEAR FOR INSPECTION AND MAINTENANCE
VS.
PERCENT EFFECTIVENESS OF MITIGATION MEASURE



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VS.
PERCENT EFFECITVENESS OF FENCE
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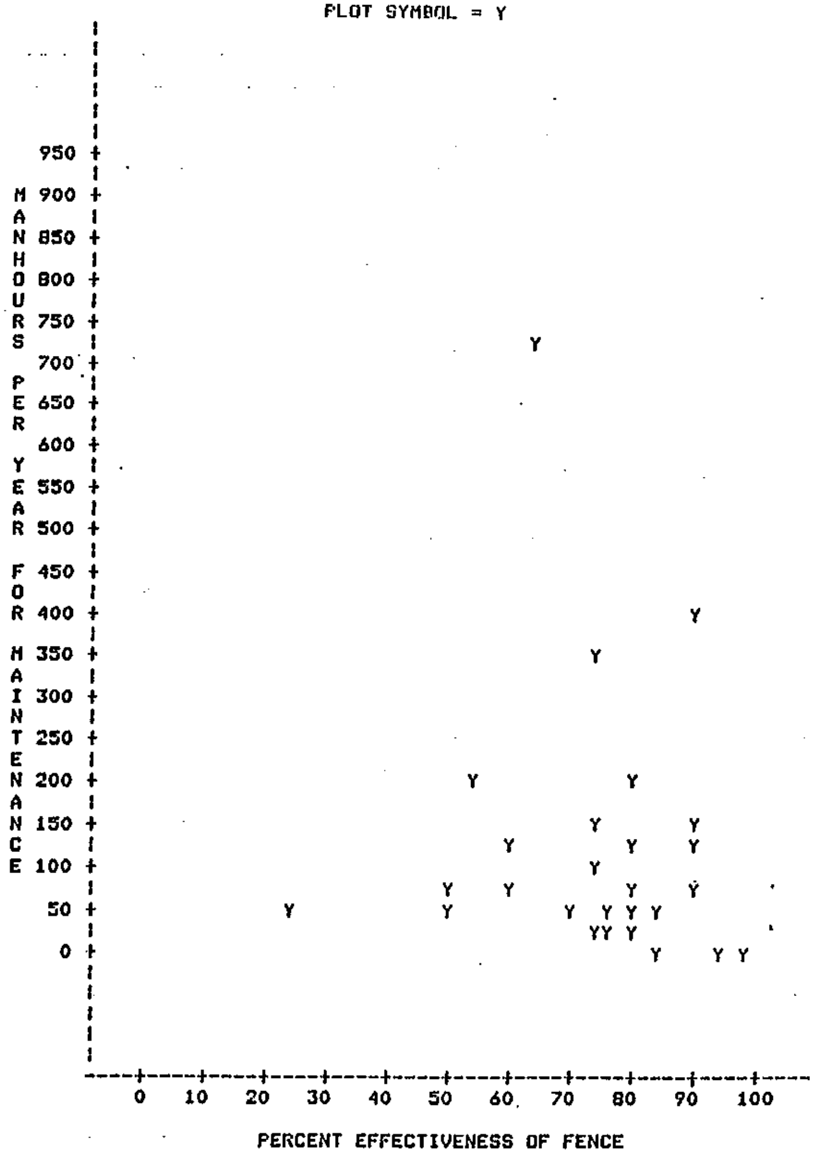

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VS.
DRAPED MESH EFFECTIVENESS
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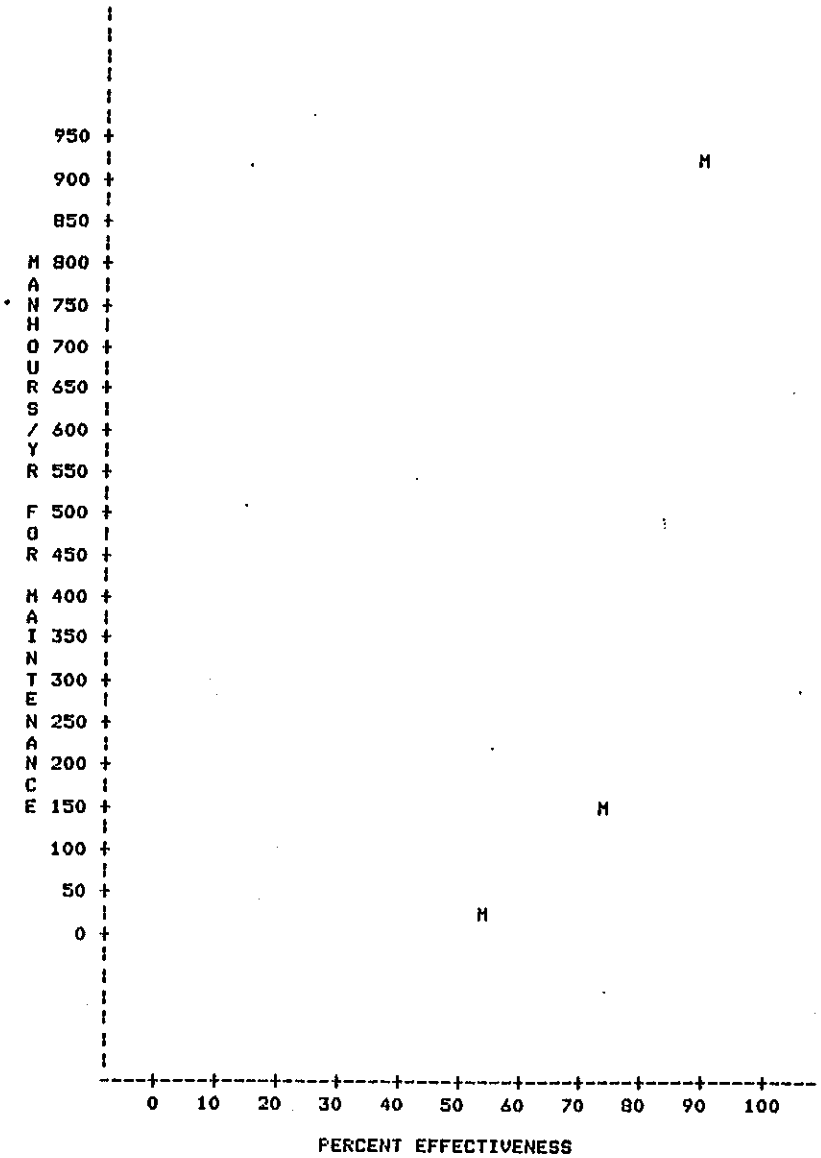

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VS.
BENCHING EFFECTIVENESS
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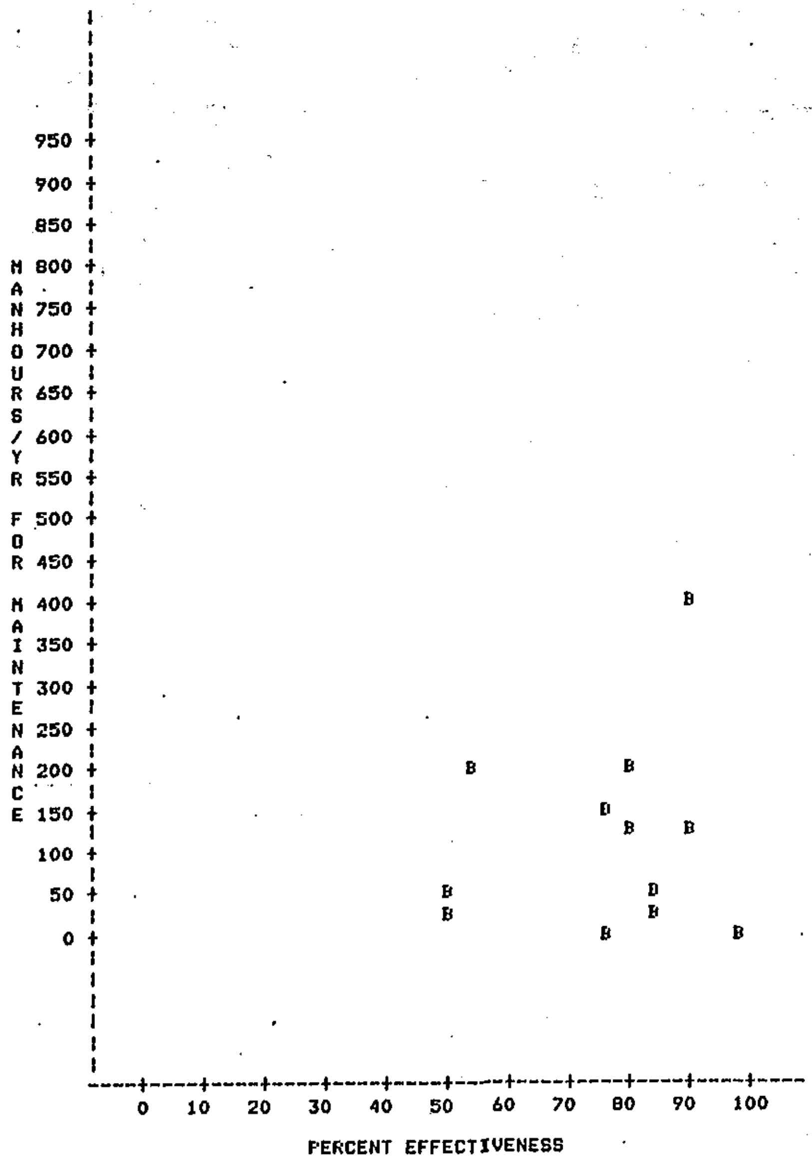

MANHOURS SPENT PER YEAR FOR INSPECTION AND MAINTENANCE
VS.
'OTHER' TYPES OF MITIGATION MEASURES EFFECTIVENESS
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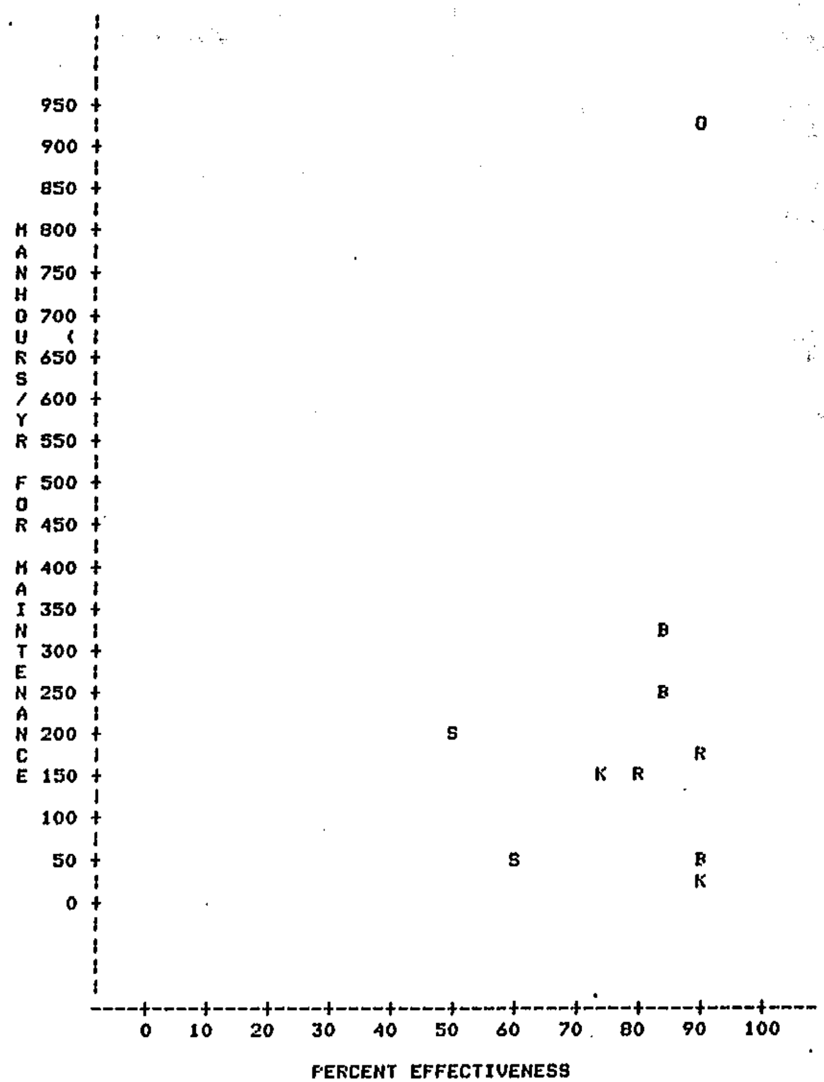
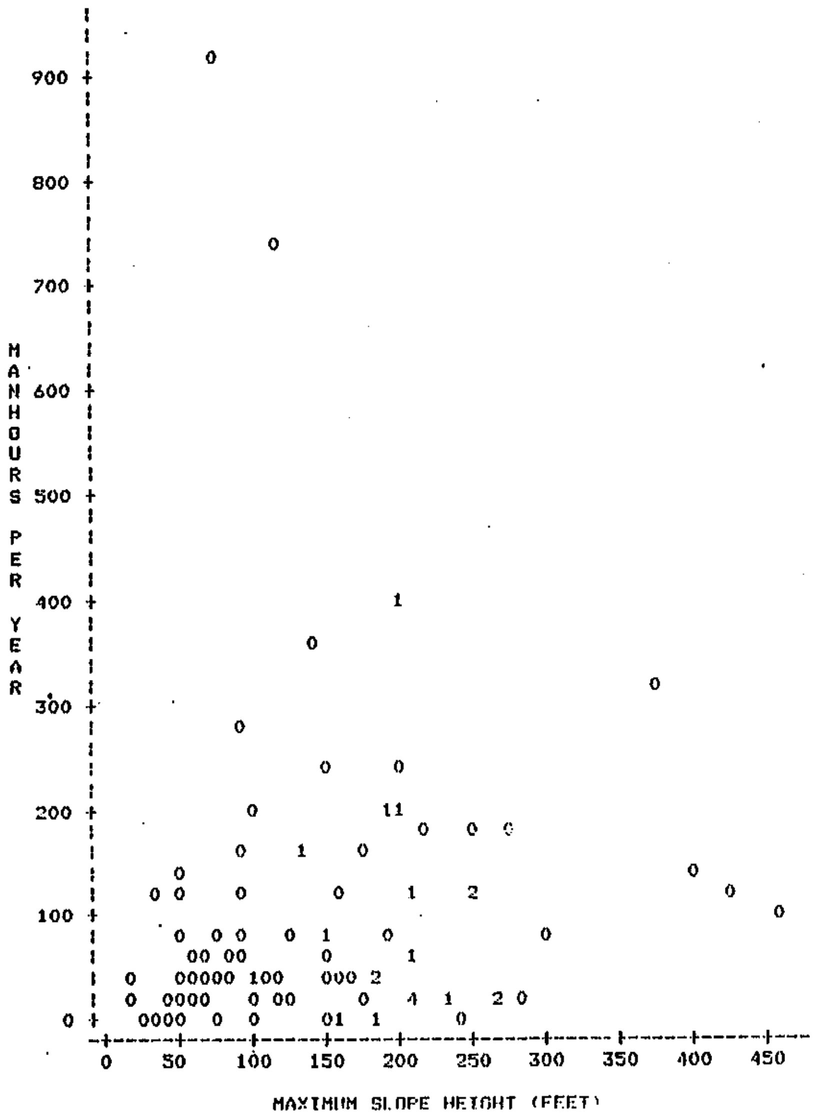
PLOT SYMBOL O=OVERHANGING FENCE
PLOT SYMBOL B=BERM
PLOT SYMBOL R=ROCKWALL

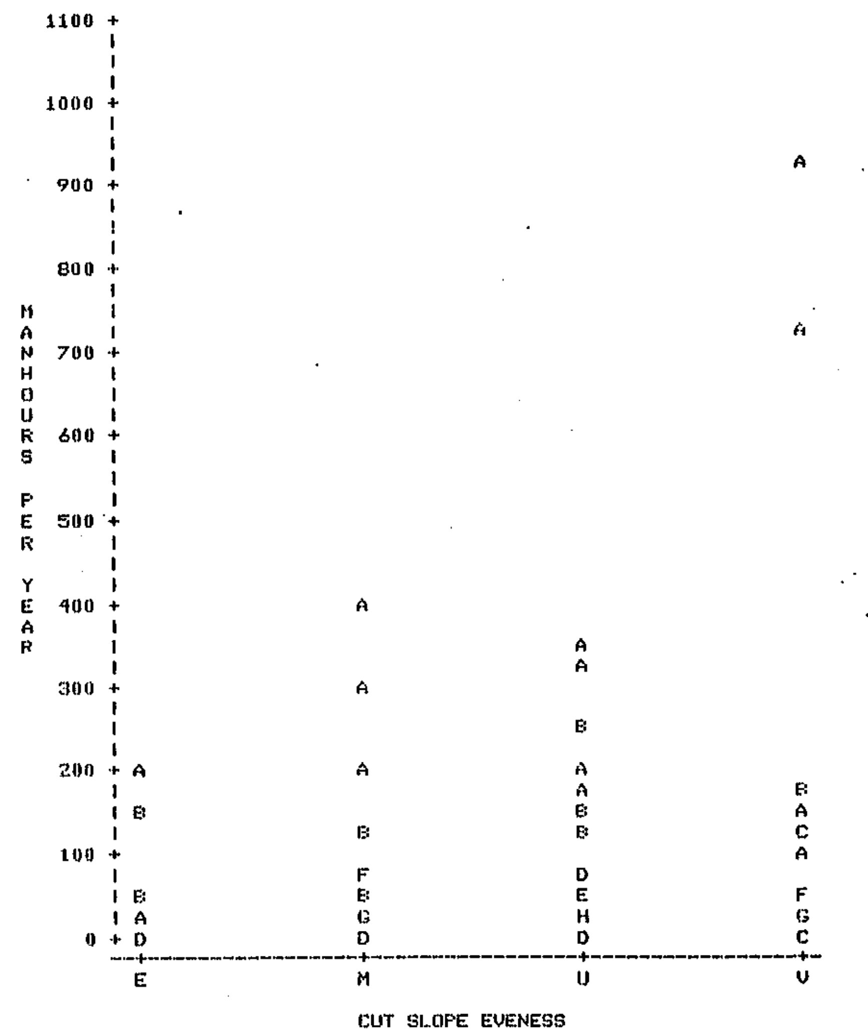


MANHOURS SPENT ON INSPECTION & MAINTENANCE OF MITIGATION MEASURE
VS.
MAXIMUM SLOPE HEIGHT(FEET)
PLOT SYMBOL=NUMBER OF BENCHES ABOVE GRADE

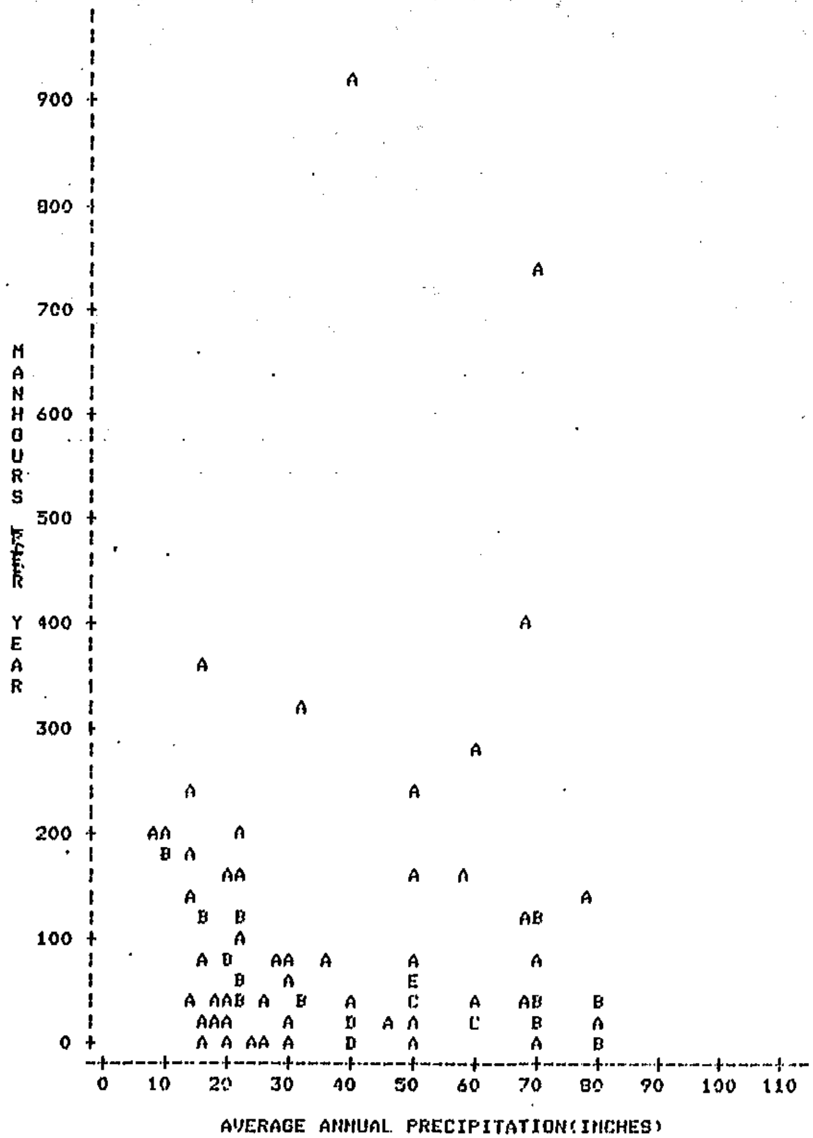


MANHOURS SPENT ON INSPECTION & MAINTENANCE OF MITIGATION MEASURE
VS.
CUT SLOPE EVENESS

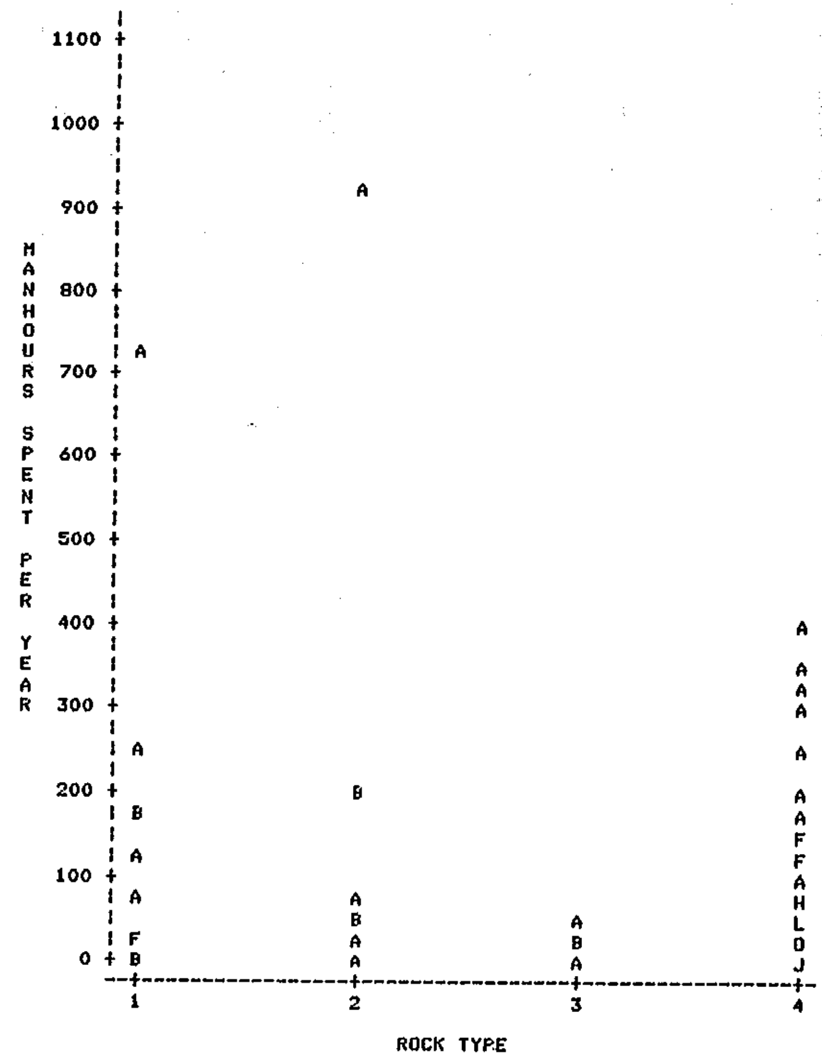
EVEN SLOPE=E
MODERATELY EVEN SLOPE=M
UNEVEN SLOPE=U
VERY UNEVEN SLOPE=V



MANHOURS SPENT ON INSPECTION & MAINTENANCE OF MITIGATION MEASURE
VS.
AVERAGE ANNUAL PRECIPITATION(INCHES)



MANHOURS SPENT PER YEAR FOR INSPECTION AND MAINTENANCE
VS.
ROCK TYPE
IGNEOUS INTRUSIVE ROCK=1
IGNEOUS EXTRUSIVE ROCK=2
METAMORPHIC ROCK=3
SEDIMENTARY ROCK=4



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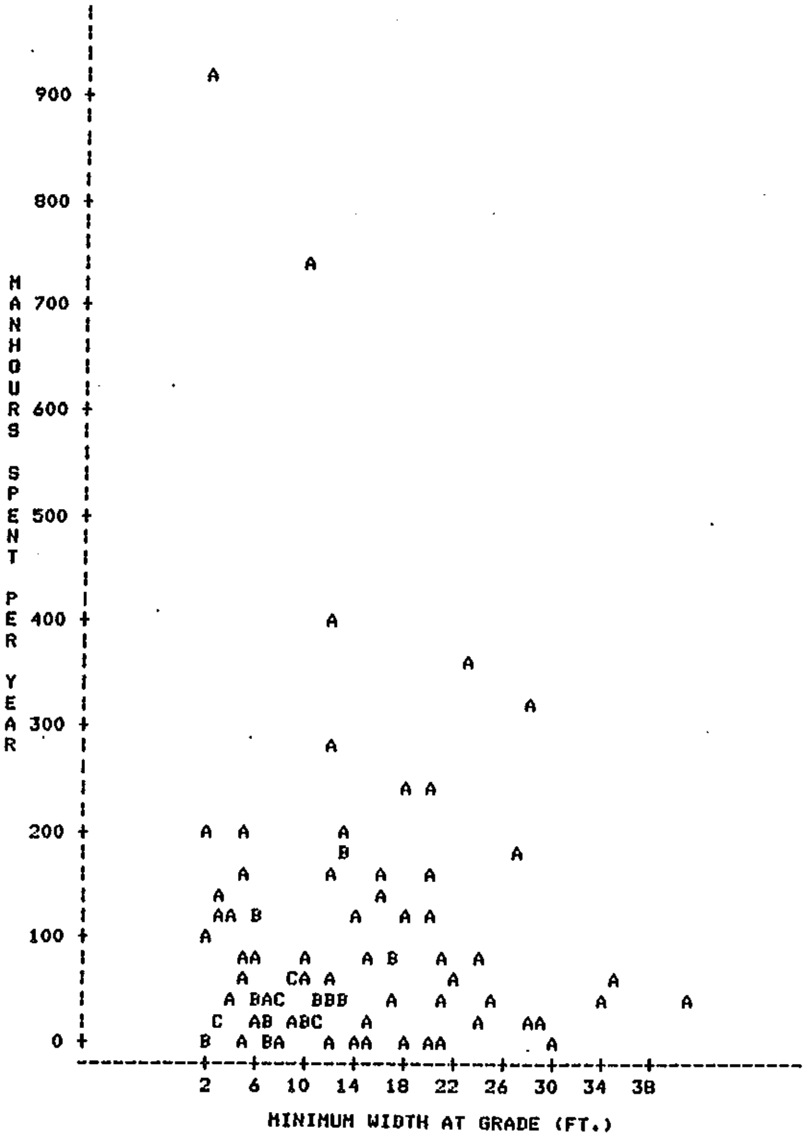
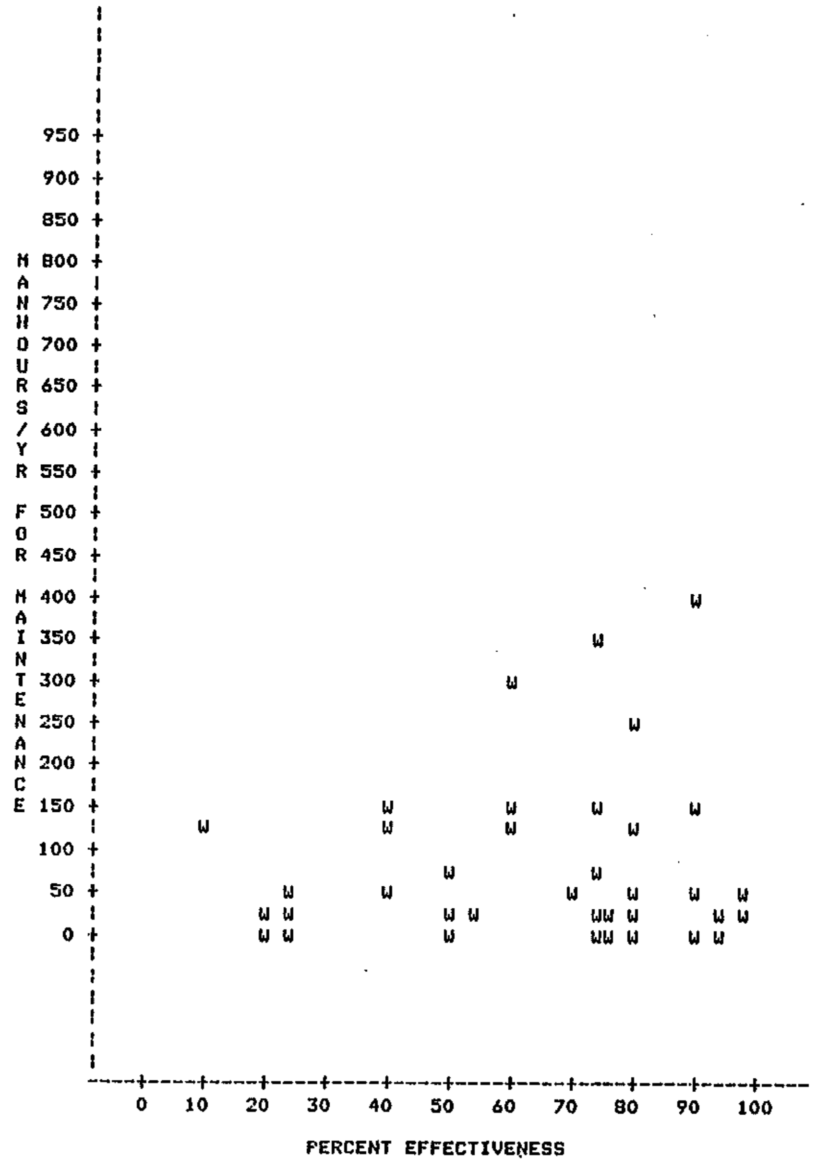
VS.
MINIMUM WIDTH AT GRADE



MANHOURS SPENT PER YEAR FOR INSPECTION AND MAINTENANCE
VS.
WIDENING EFFECTIVENESS
PLOT SYMBOL=W



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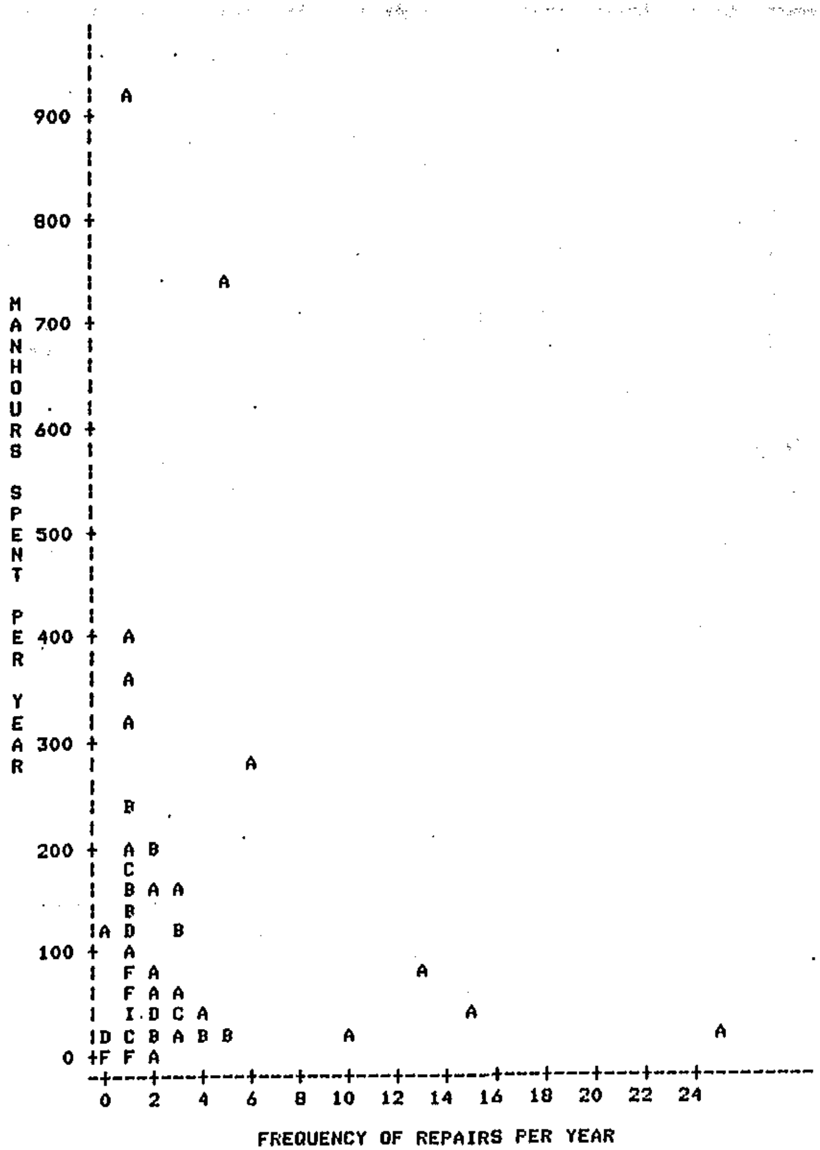
VS.
FREQUENCY OF REPAIRS TO MITIGATION PER YEAR



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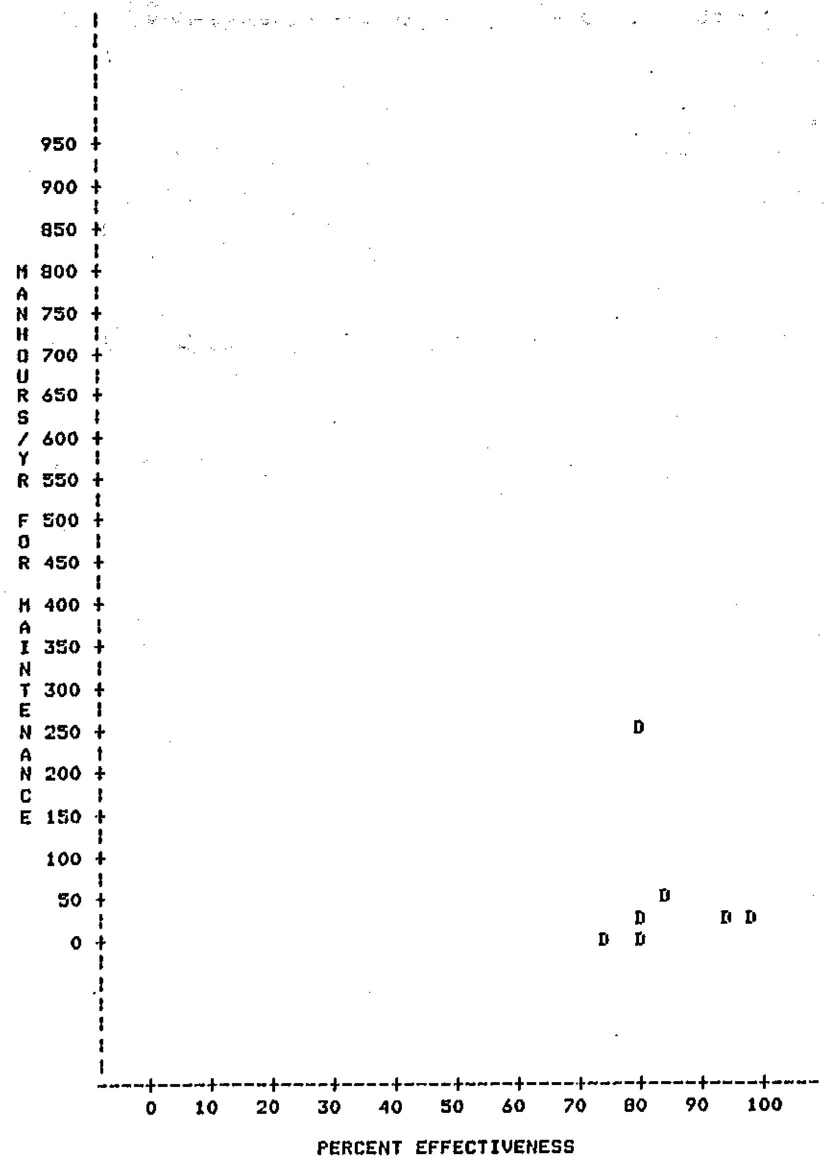
VS.
DITCH EFFECITVENESS
PLOT SYMBOL=D



MANHOURS SPENT PER YEAR FOR INSPECTION AND MAINTENANCE
VS.
MINIMUM DISTANCE FROM TOE TO FENCE